VOLUME 106 PART A NUMBER 29 OCTOBER 1959

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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containing the full account of the

CONVENTION ON THERMONUCLEAR PROCESSES

held at The Institution on 29th and 30th April, 1959

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CONVENTION ON THERMONUCLEAR PROCESSES

CONTENTS

1 The Development of Thermonuclear Devices in Britain

2 Construction Features of Zeta

3 Contributions from the U.S.A. and U.S.S.R.

4 Engineering Design Problems Associated with New Systems

5 The Constricted Plasma and its Future

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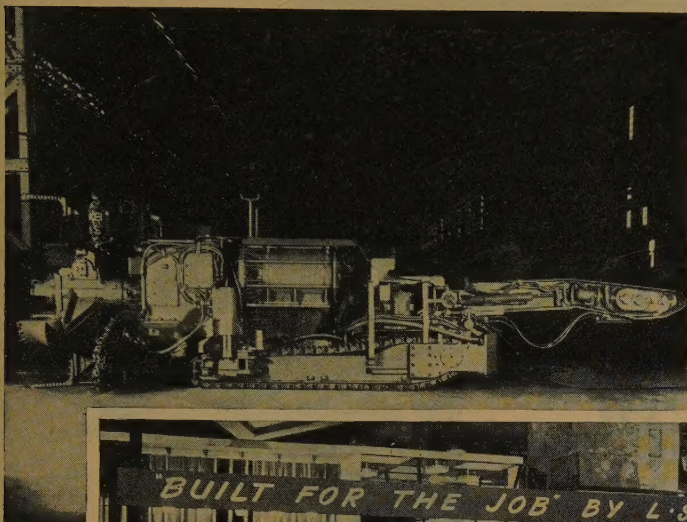

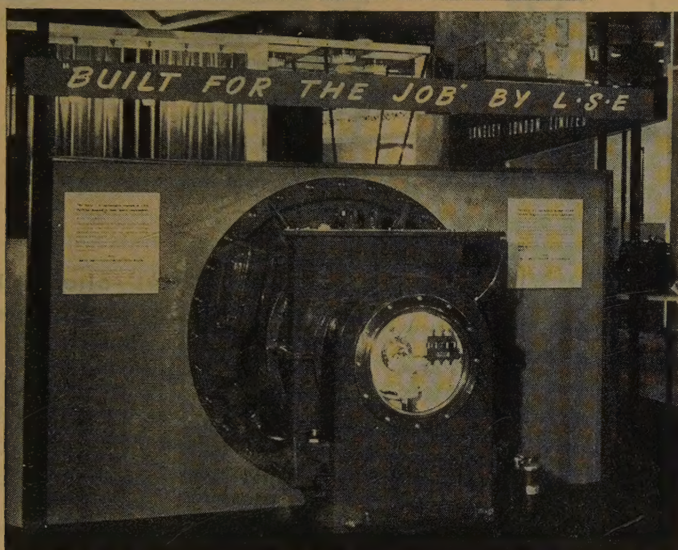

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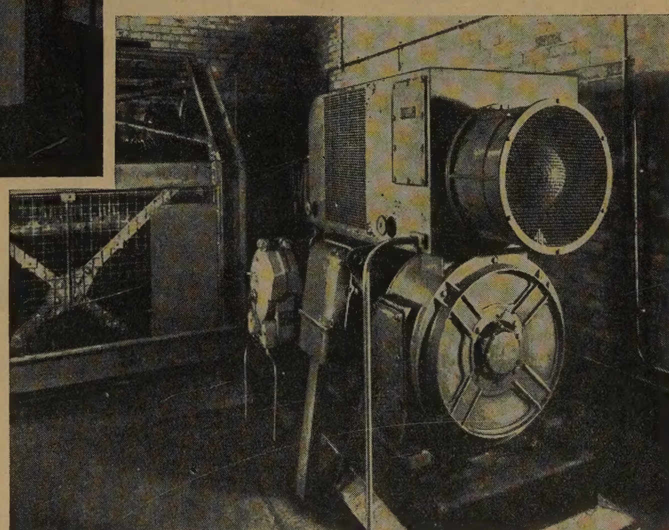

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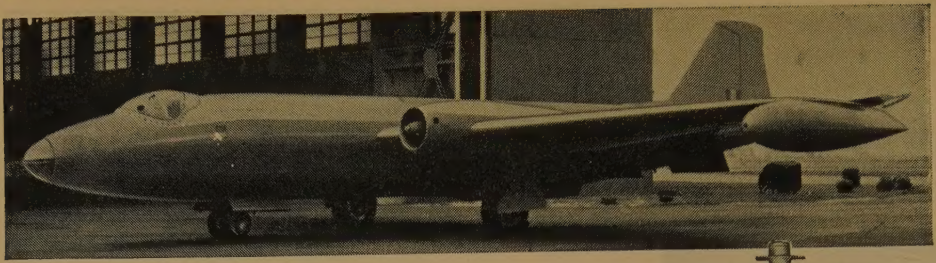

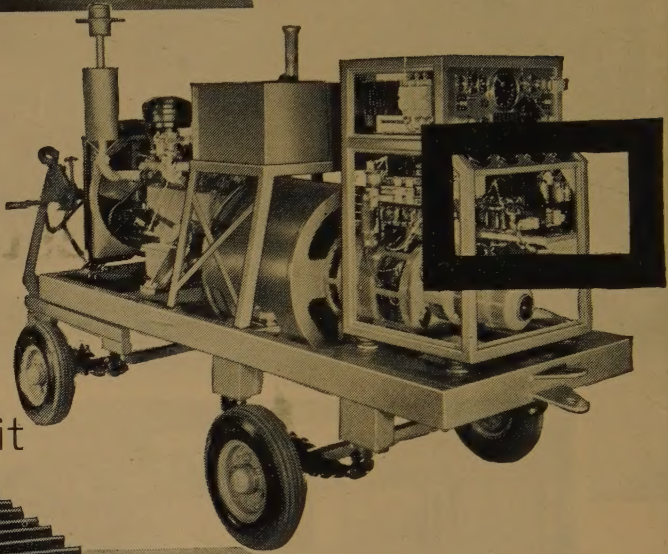

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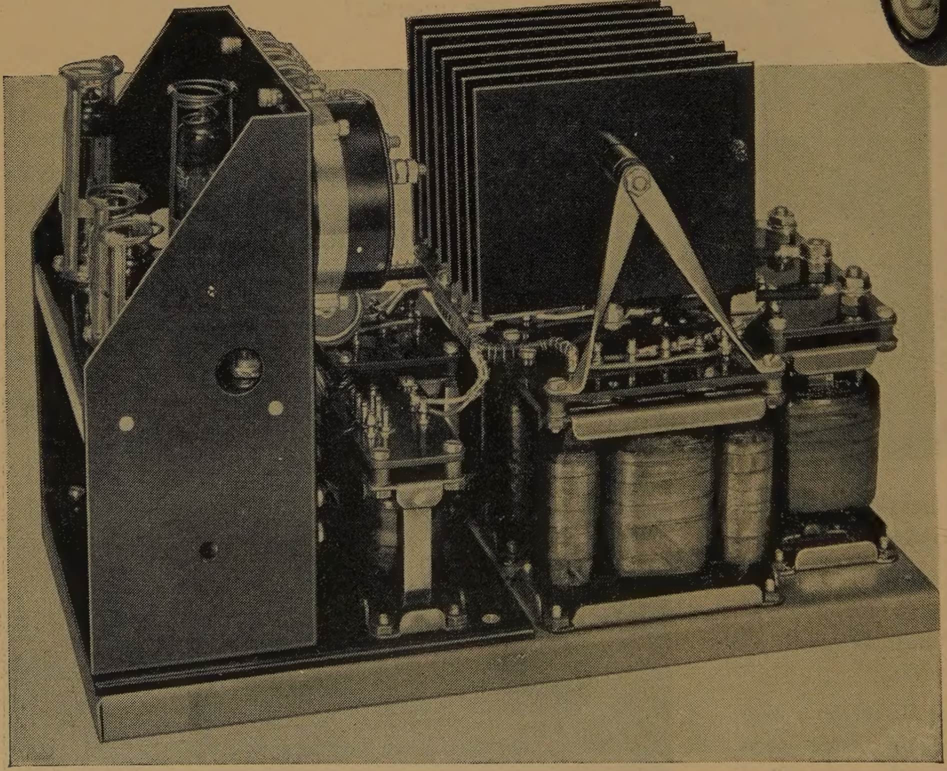

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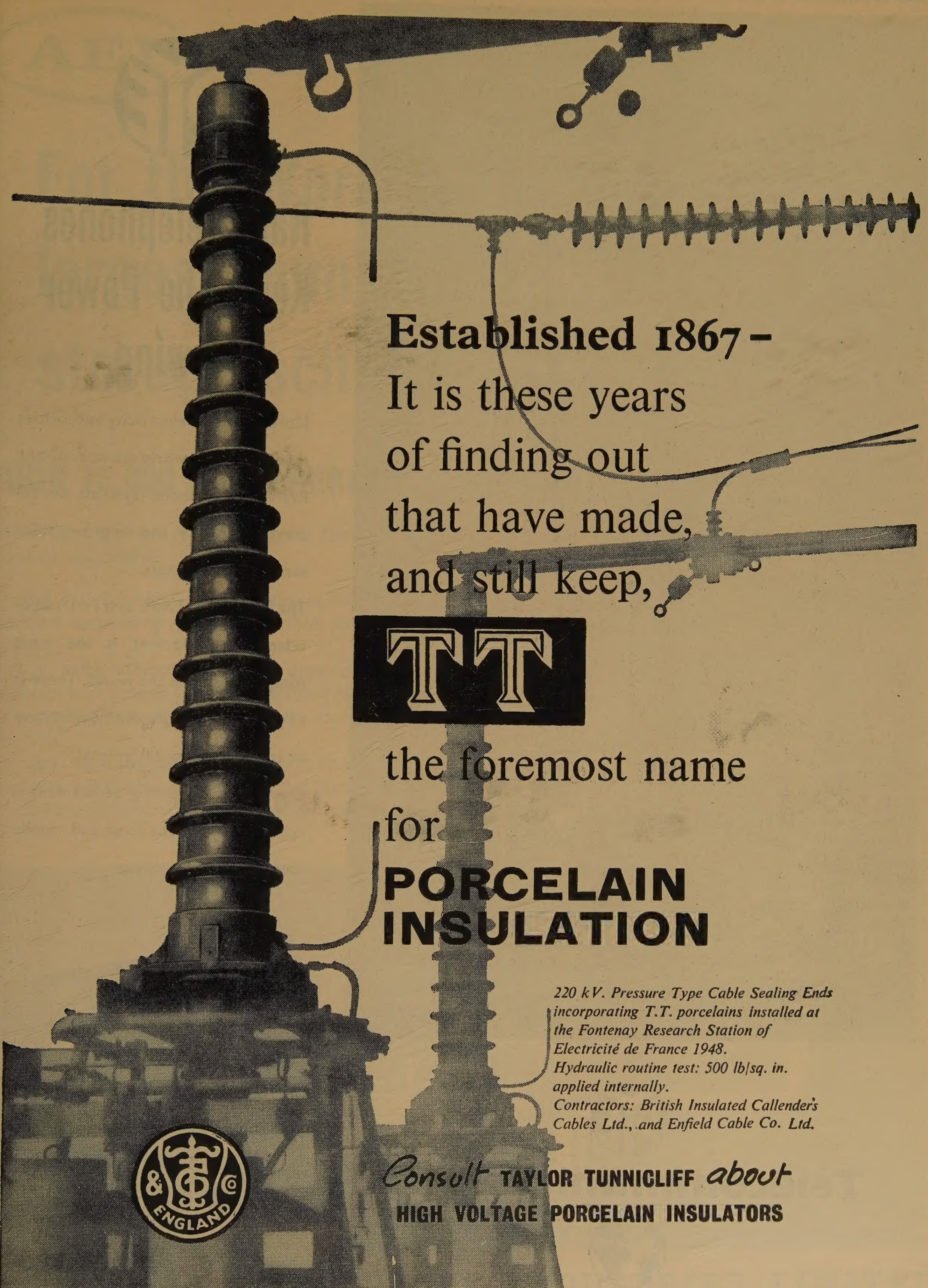

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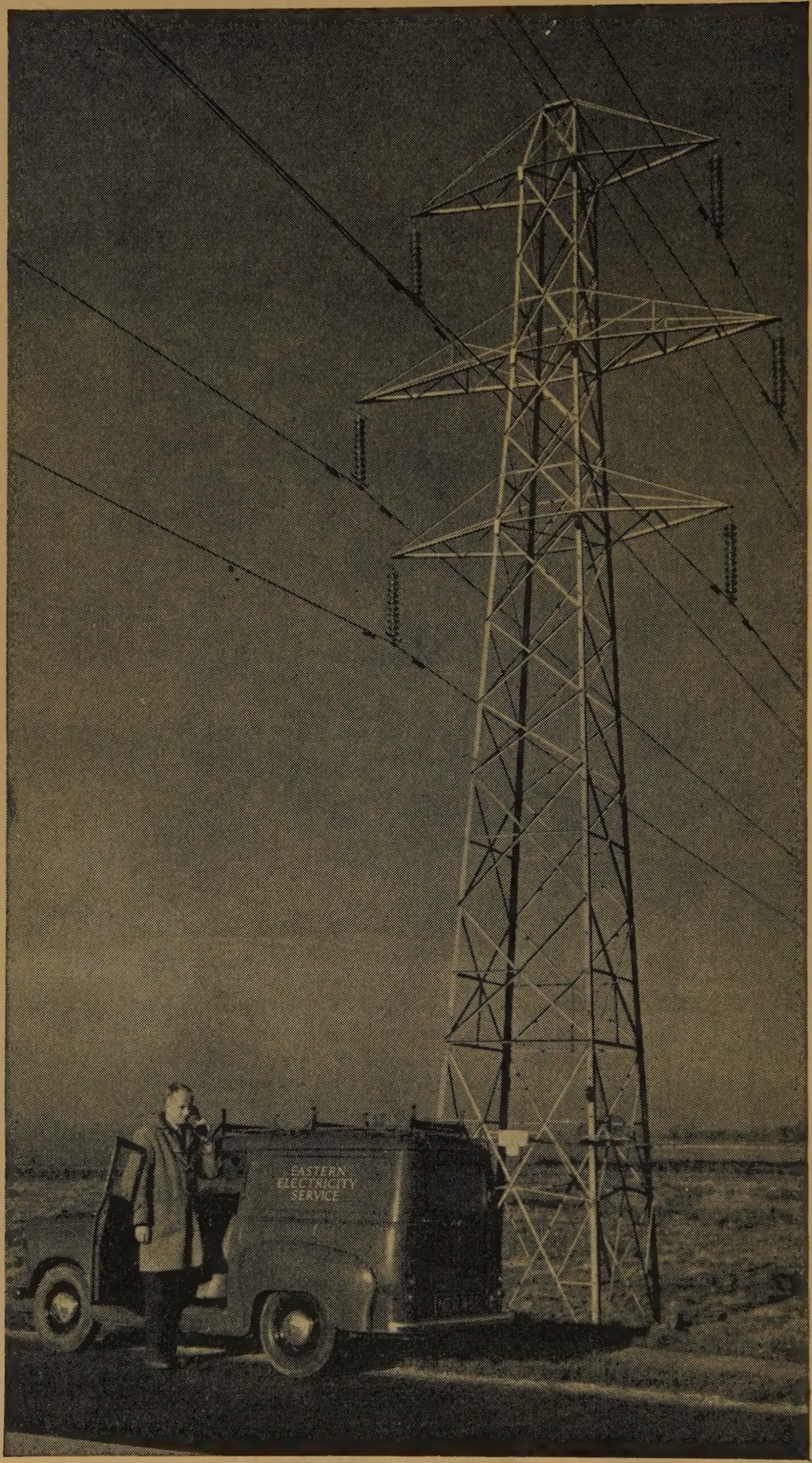

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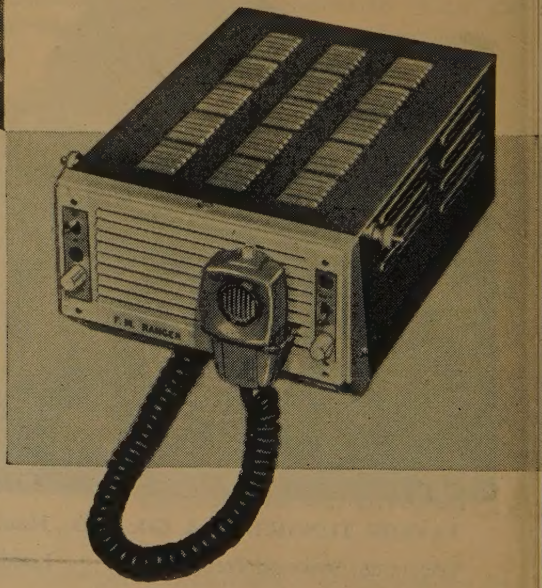

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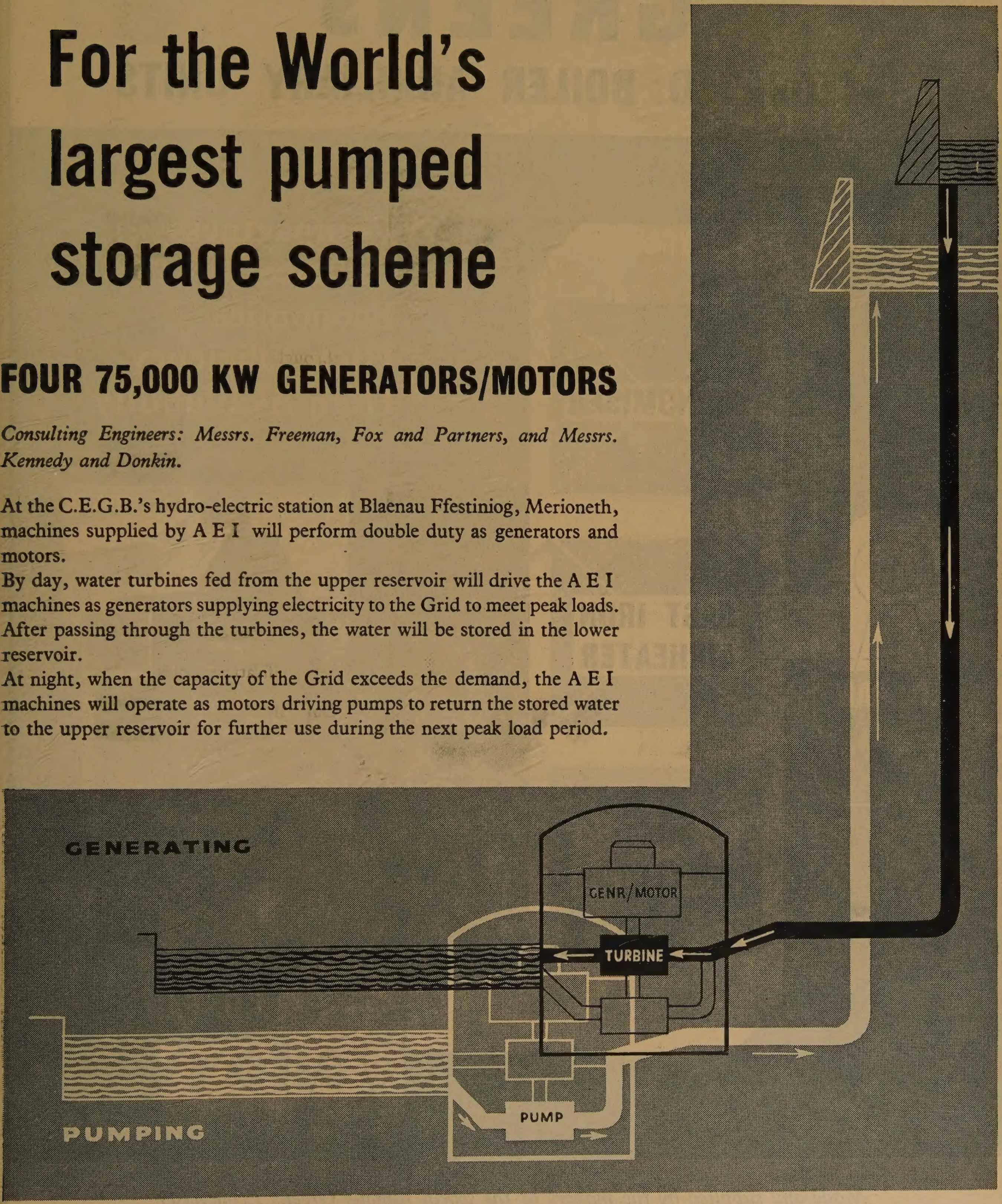

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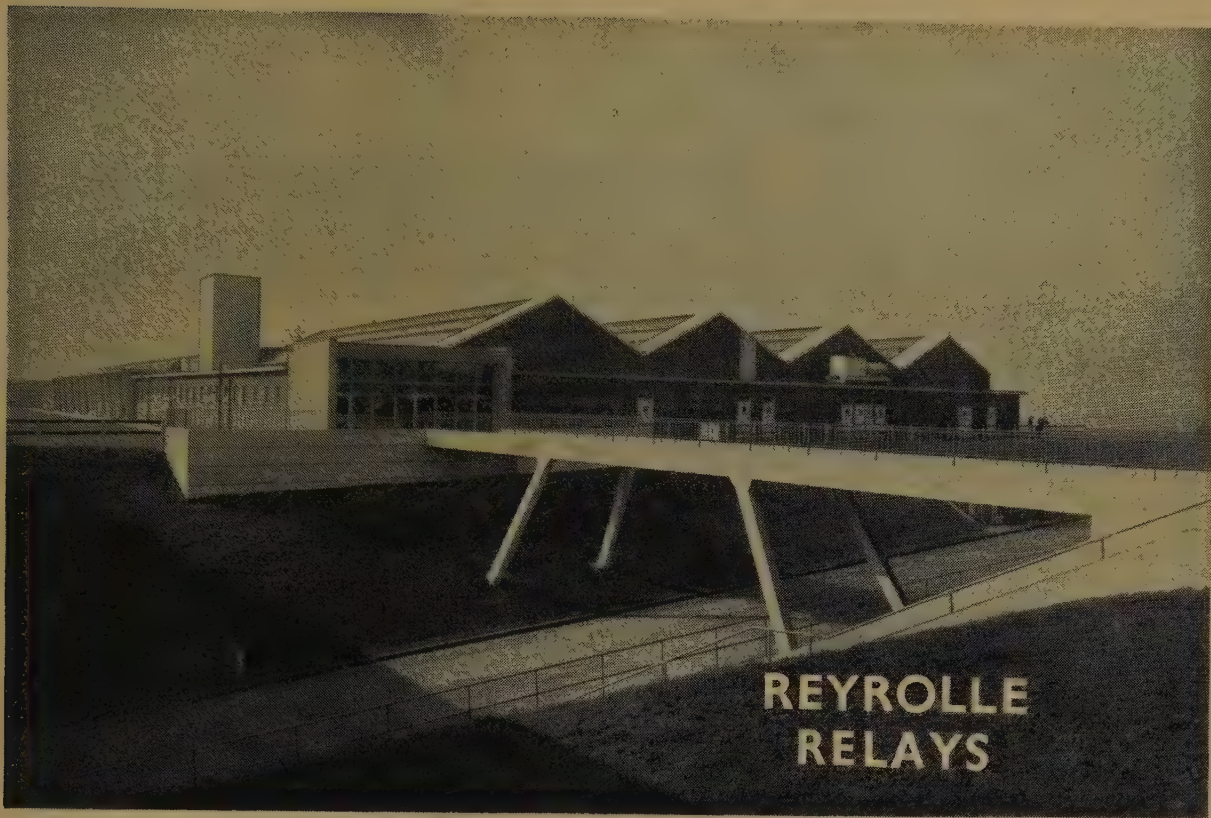

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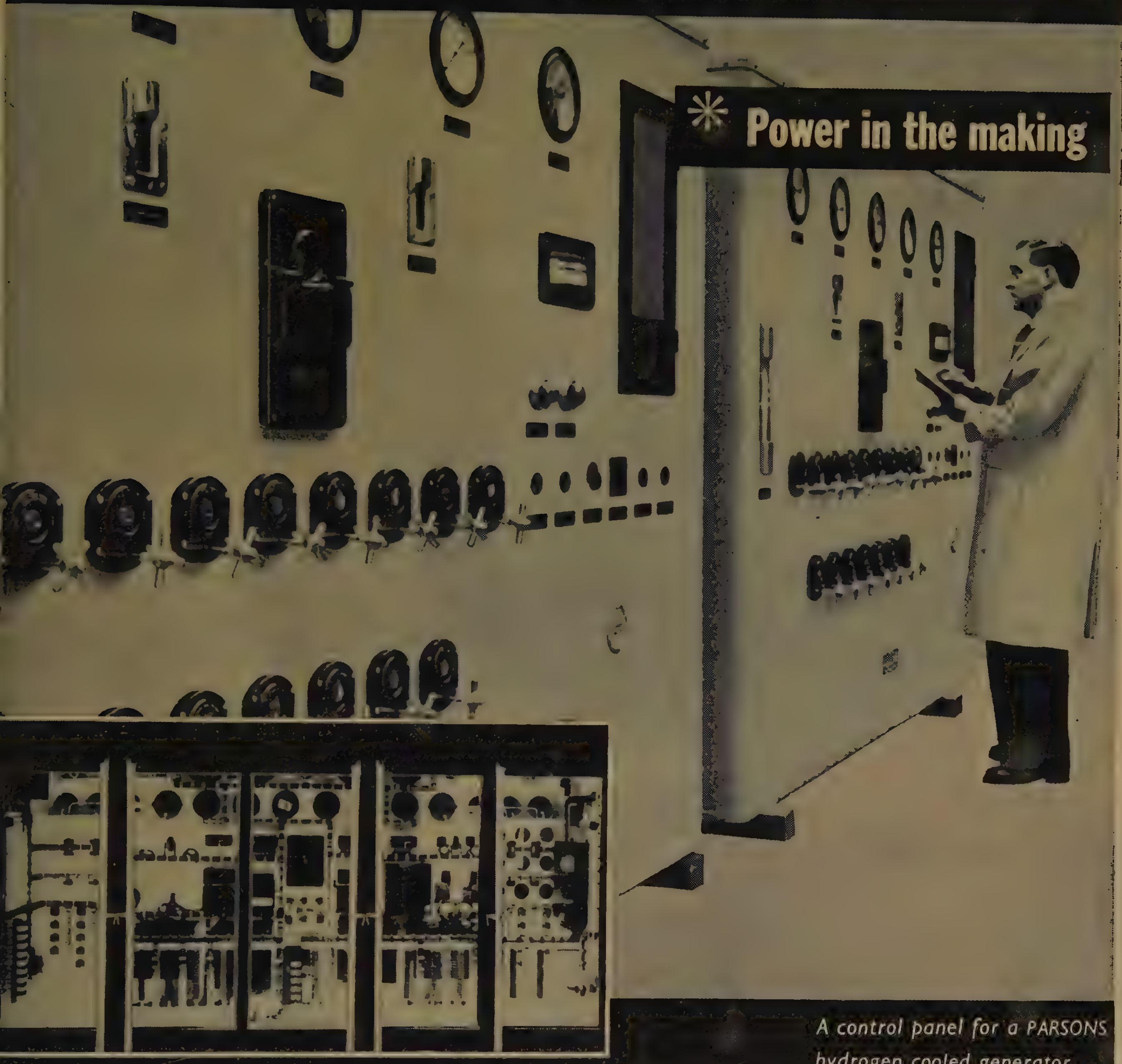

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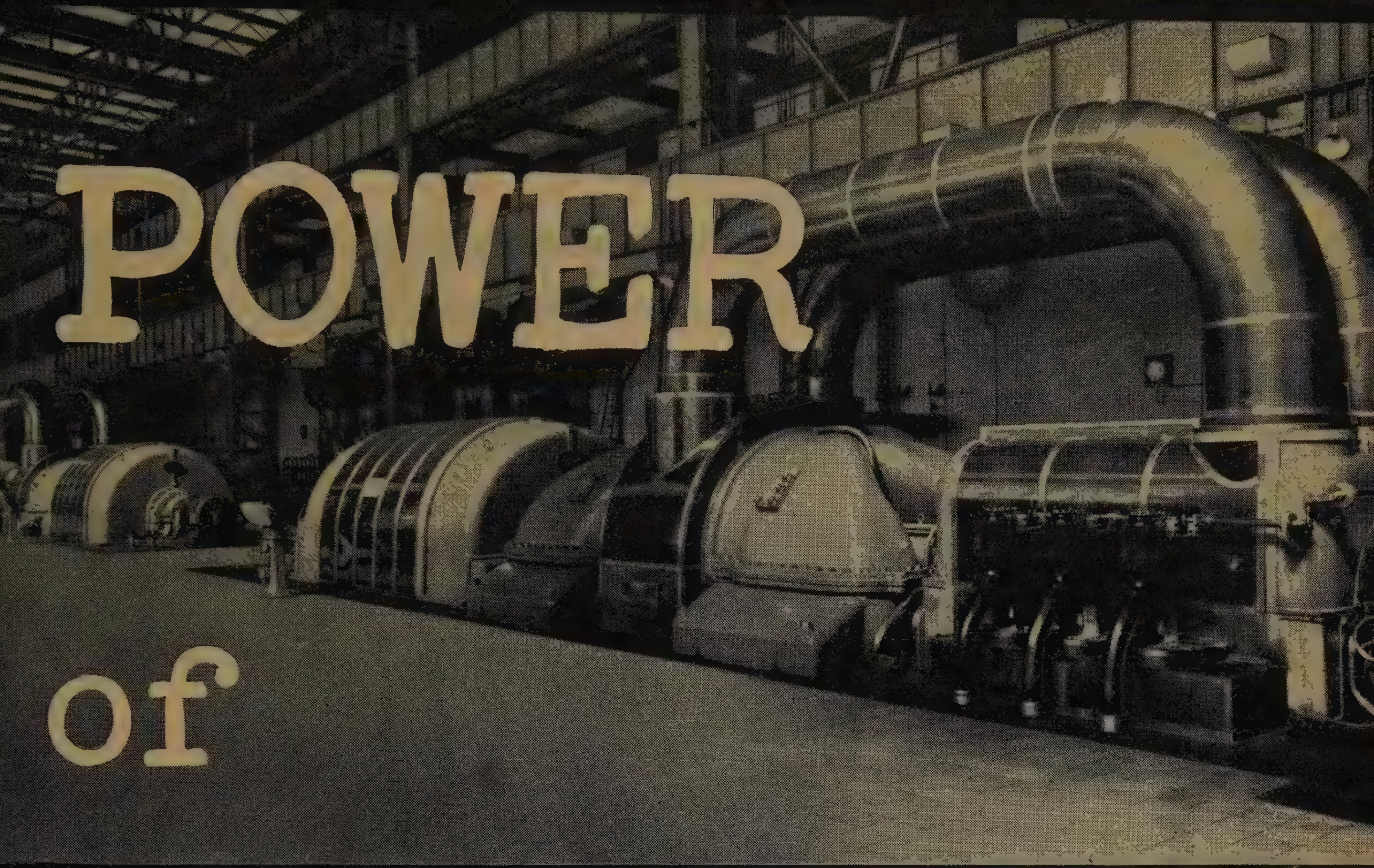

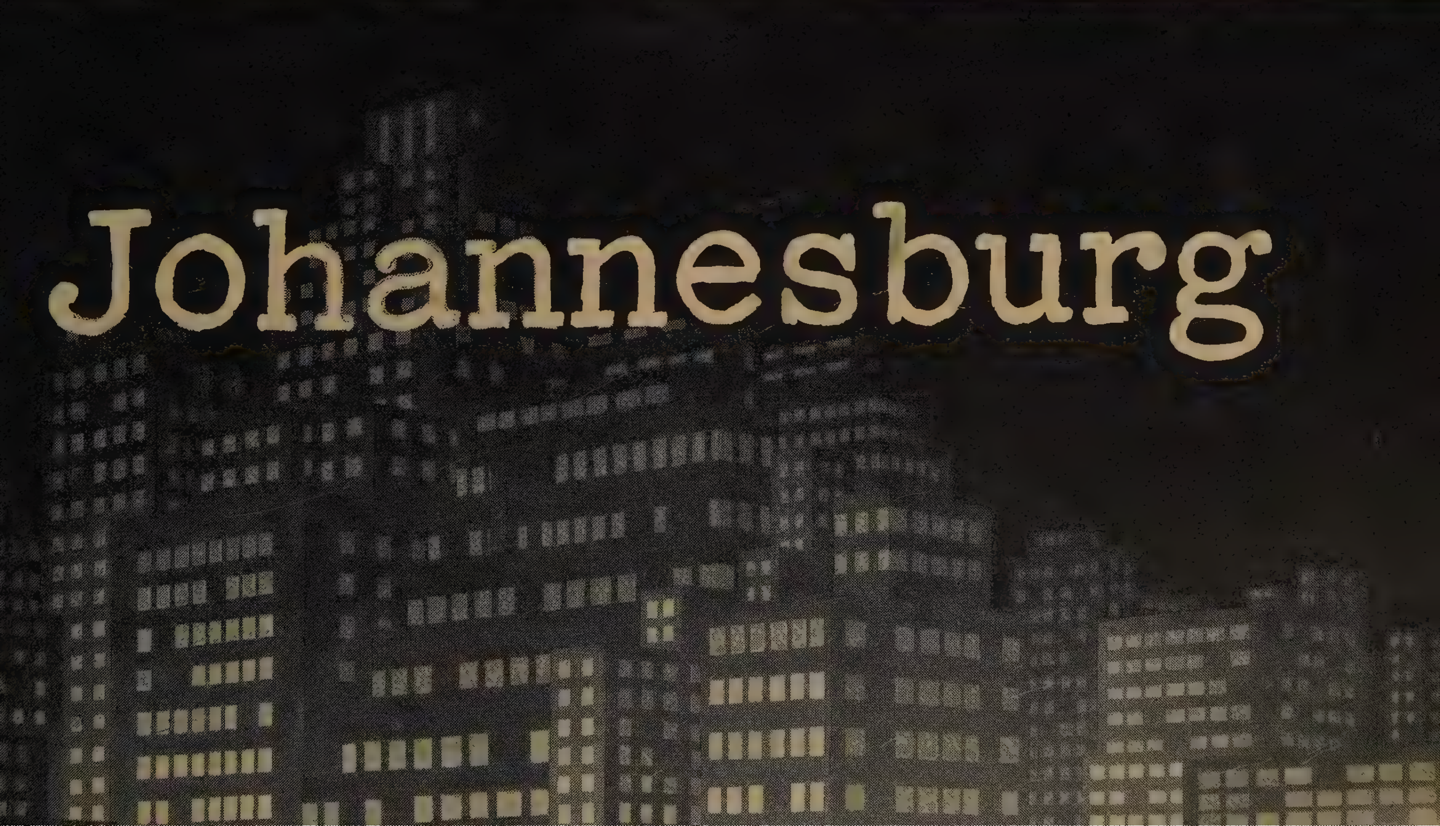

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Close up and general views of Hackbridge and Hewittic type RVB and RDB 33 kV isolators installed at Shepreth Substation, Eastern Electricity Board.

Illustrated right:
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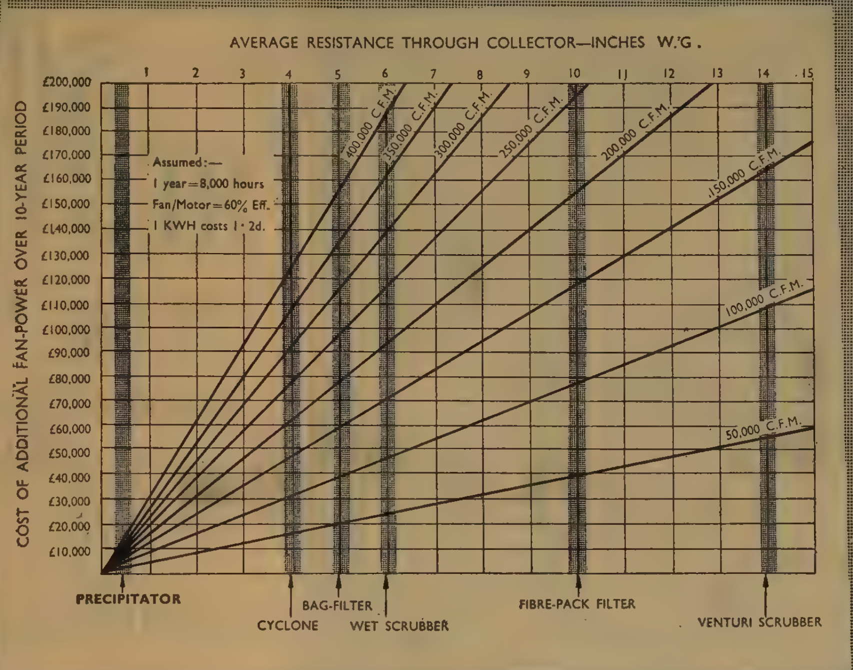

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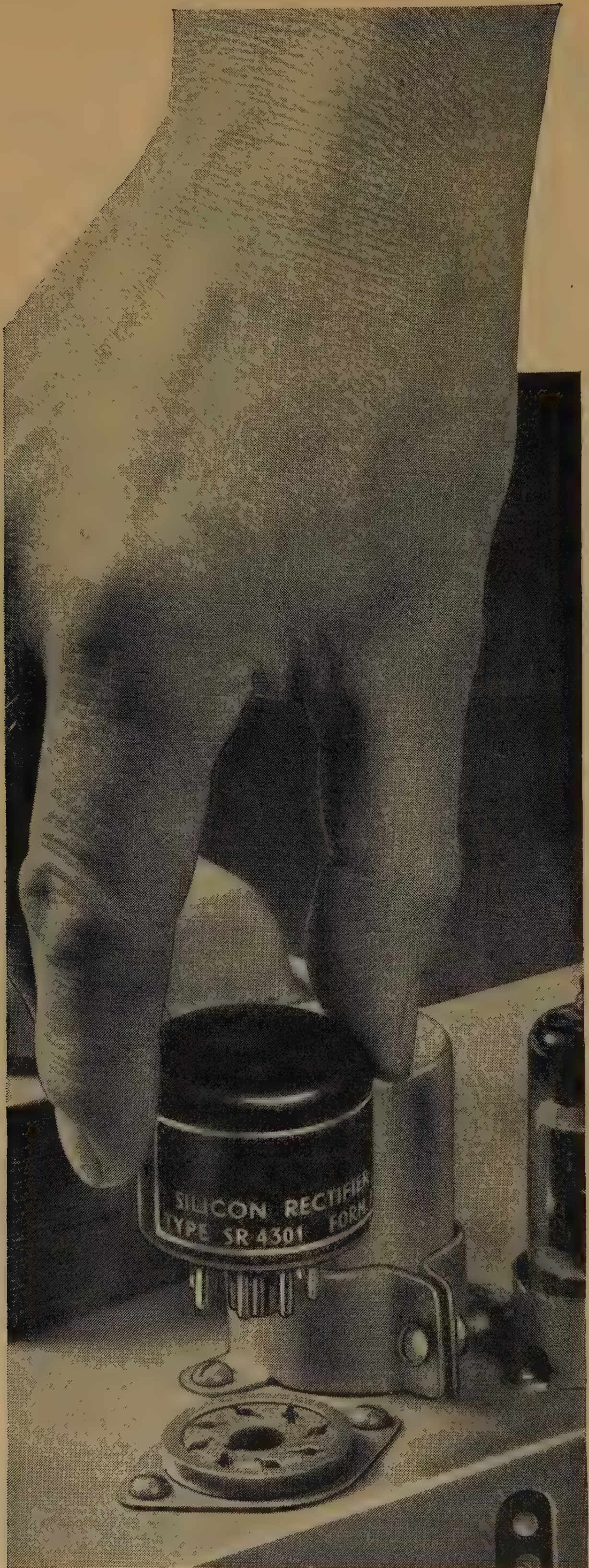

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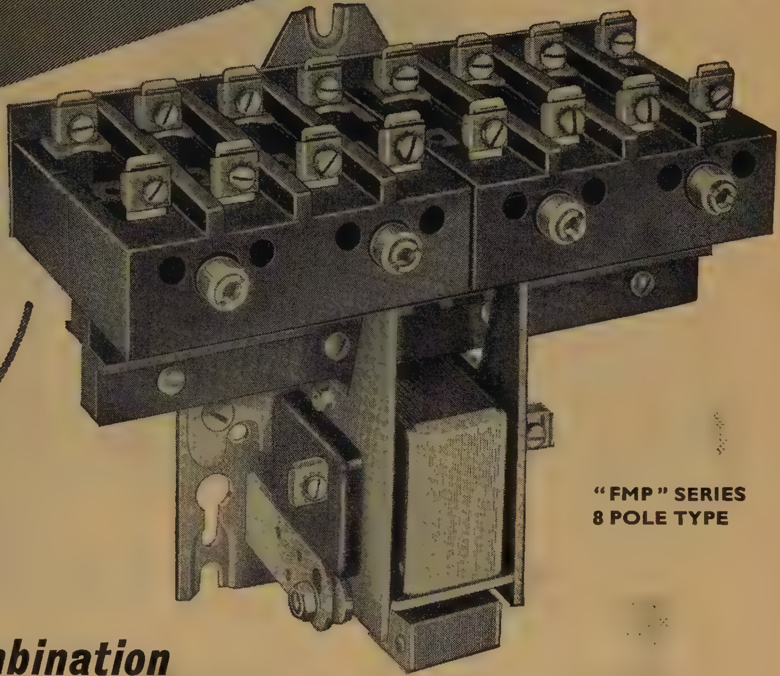

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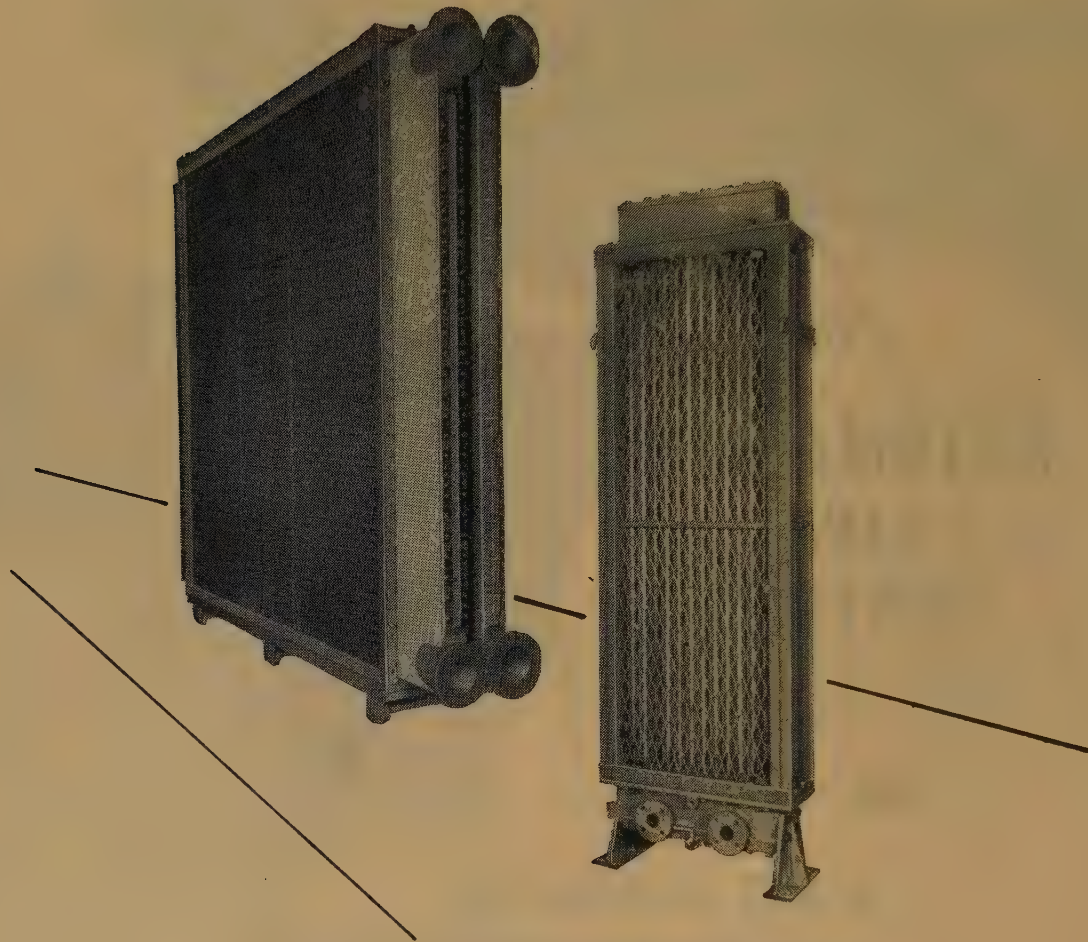

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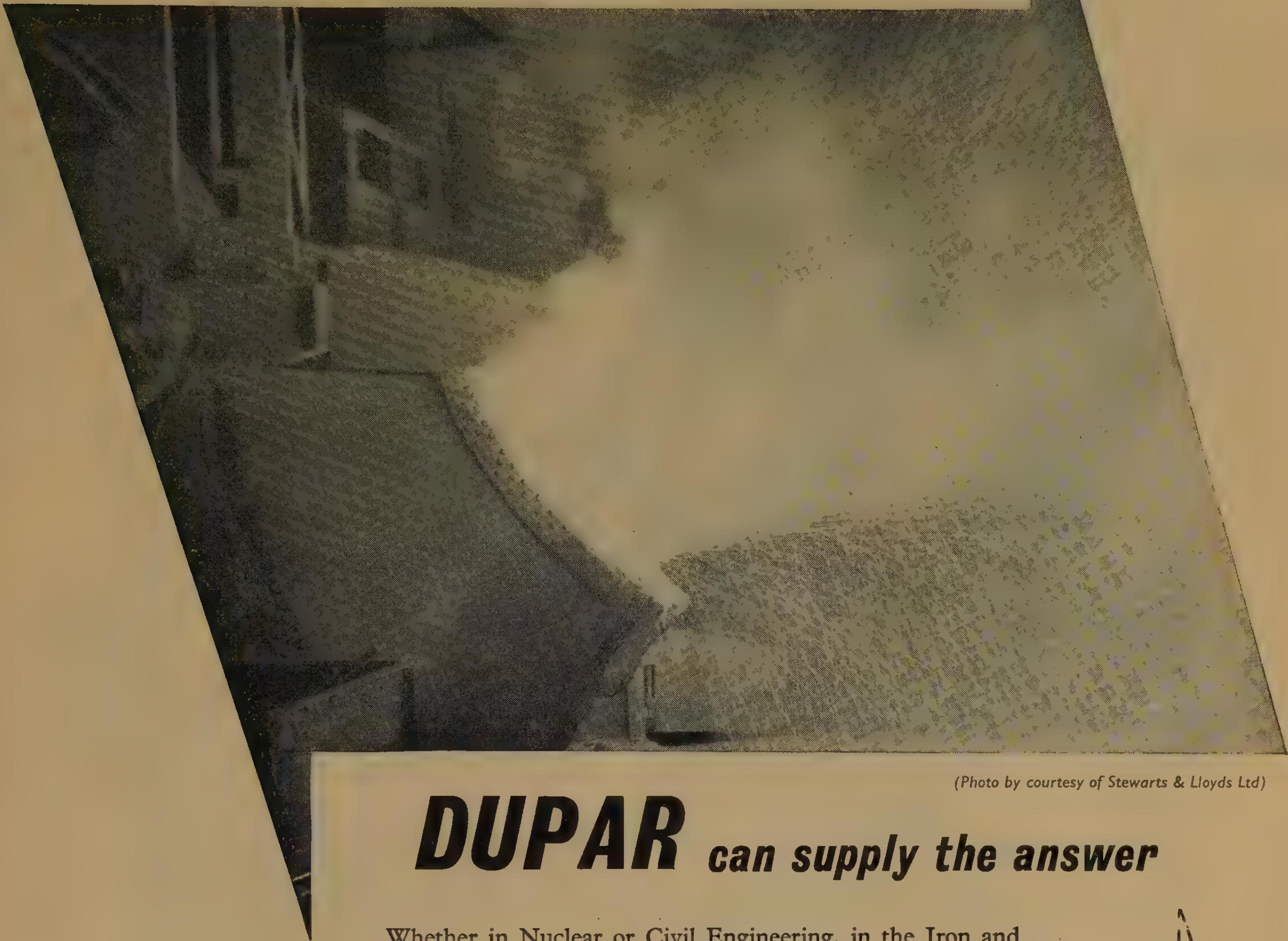

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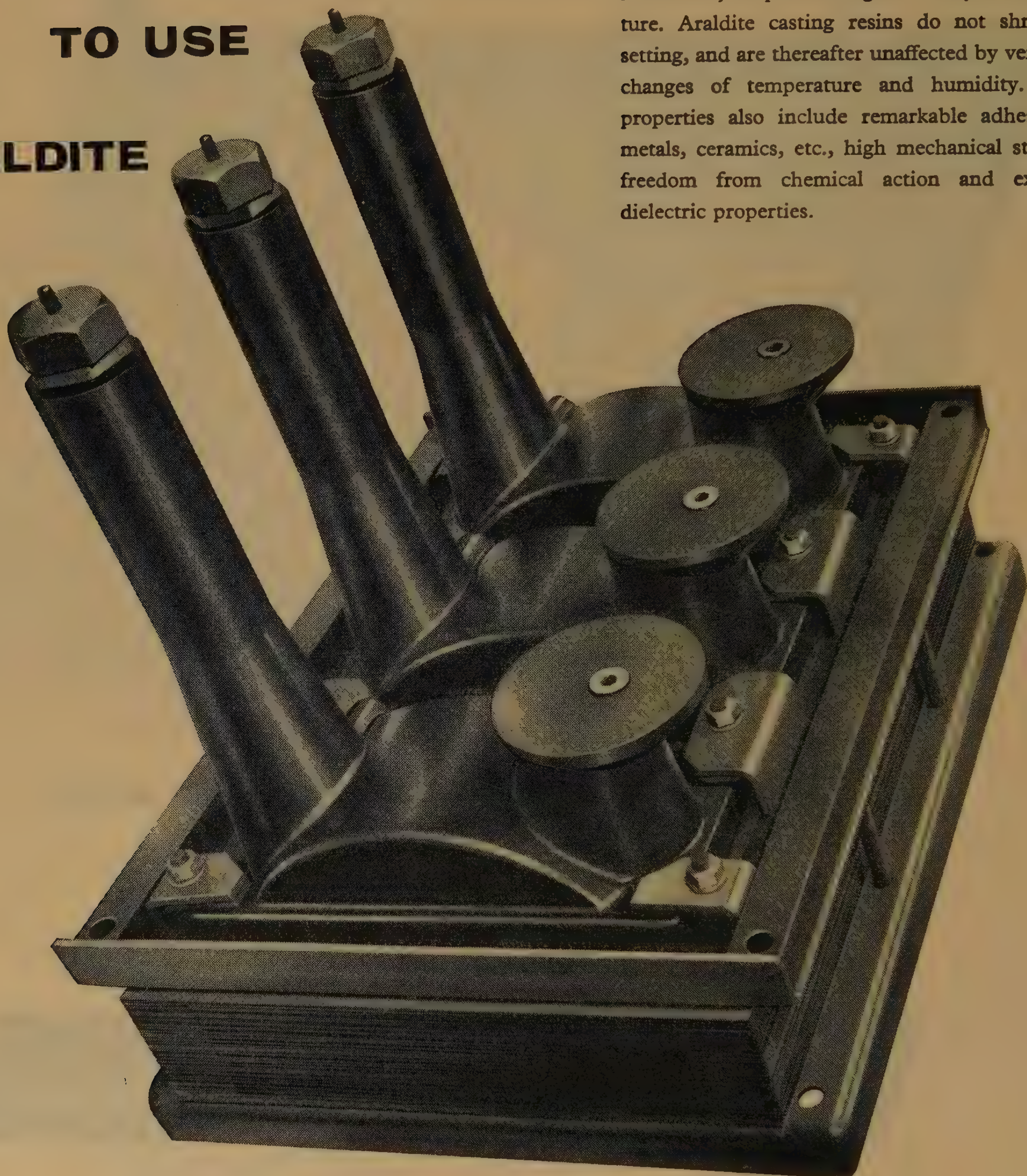

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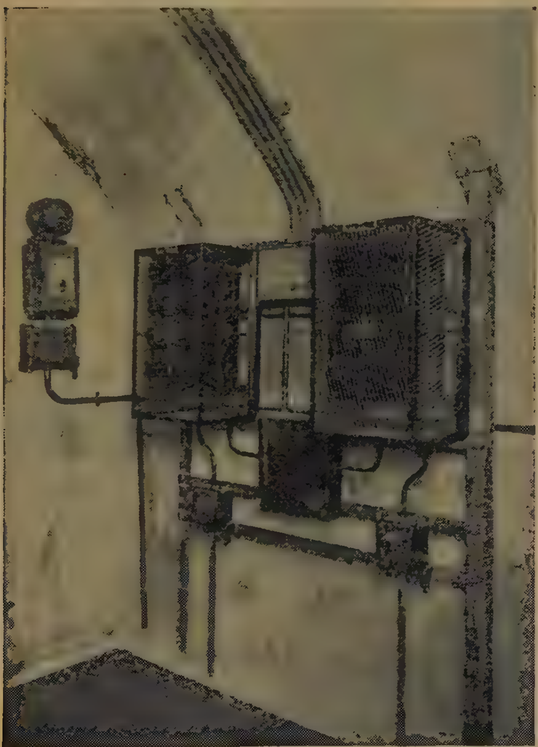
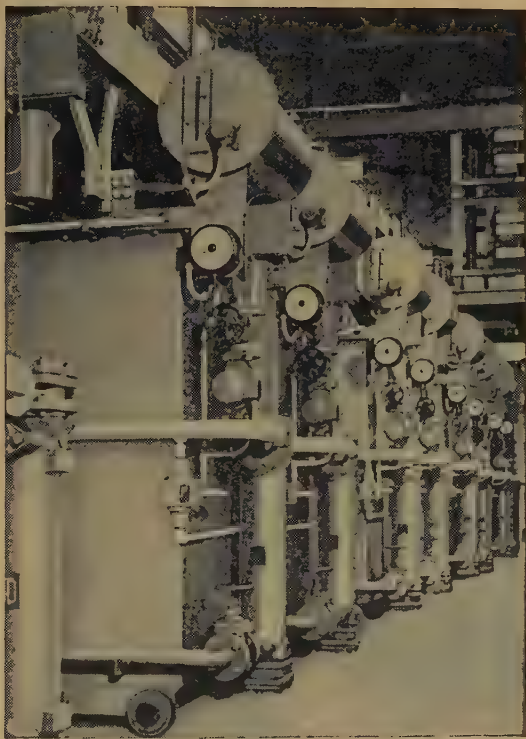


1932 *Two copper-oxide rectifiers supplying power to variable speed motors at the Bruton Club.*



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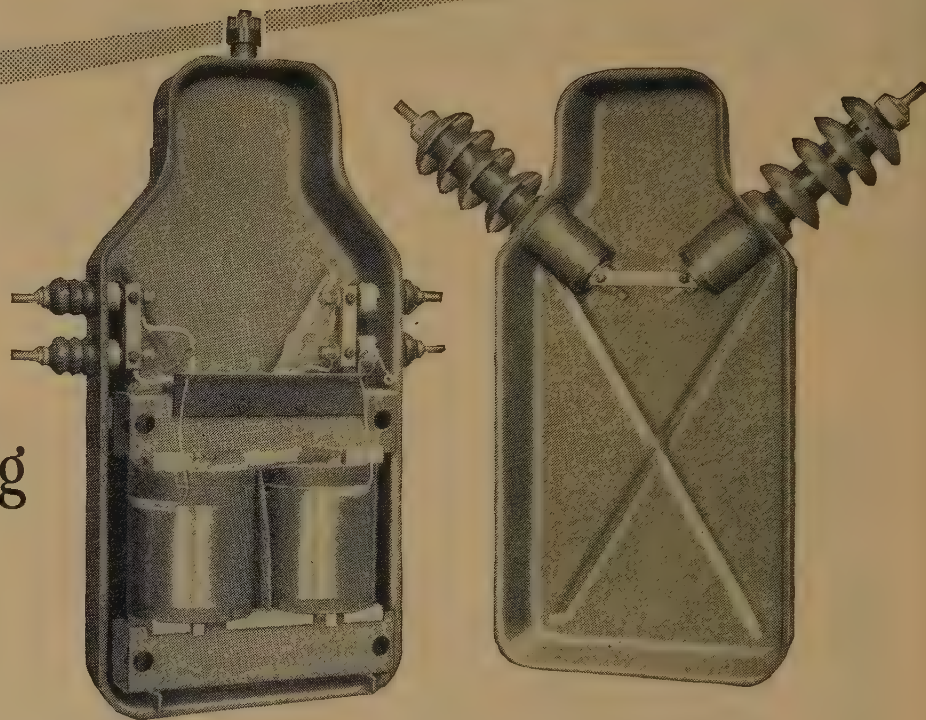

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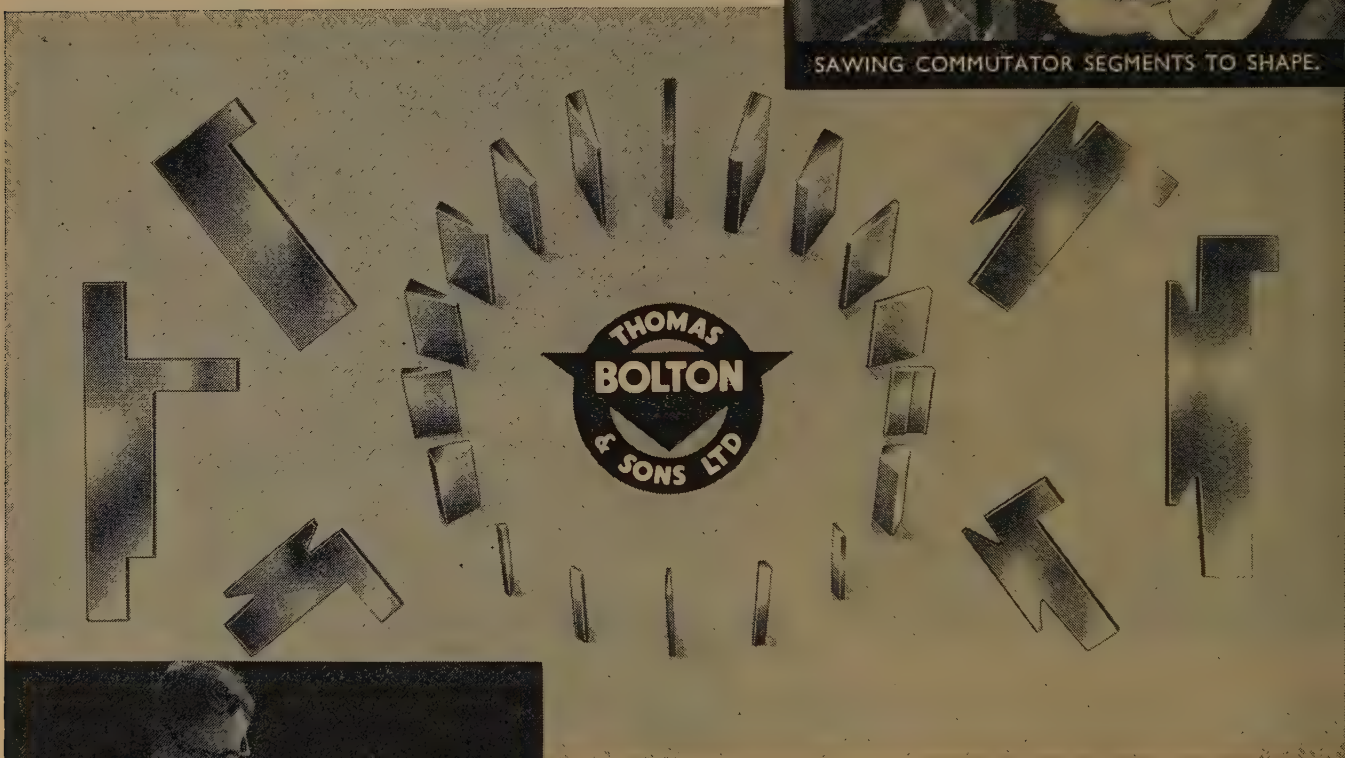

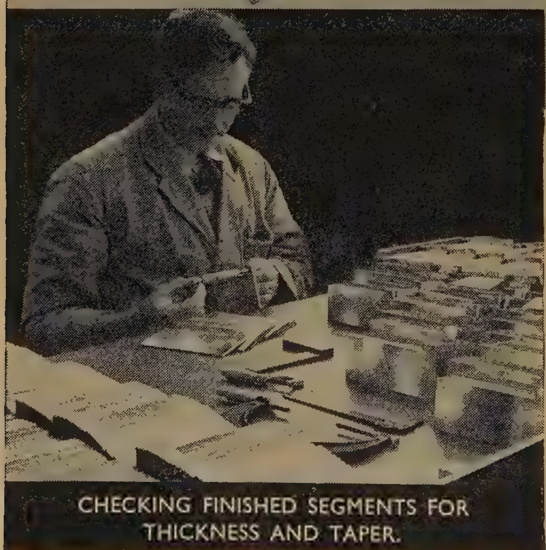
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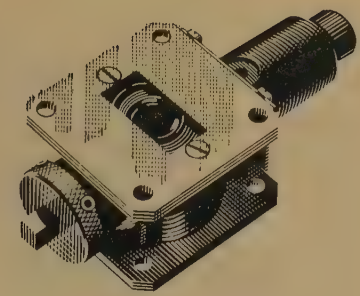

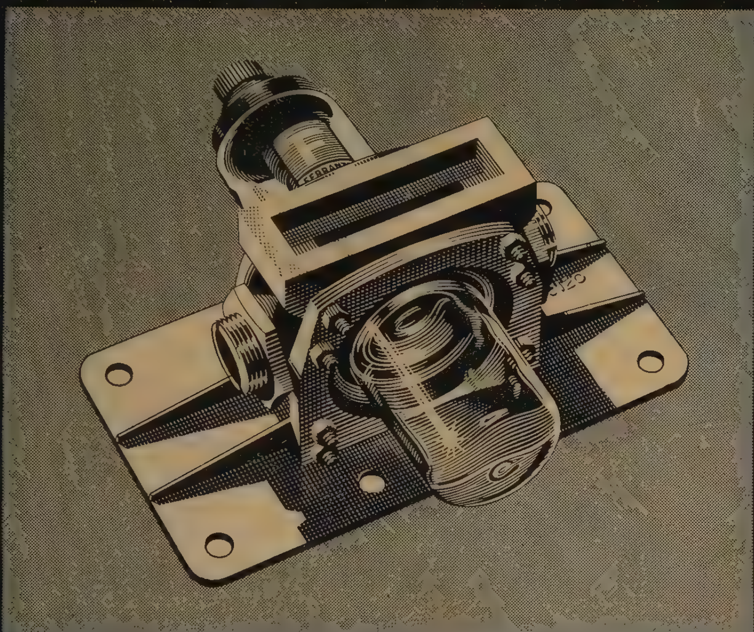

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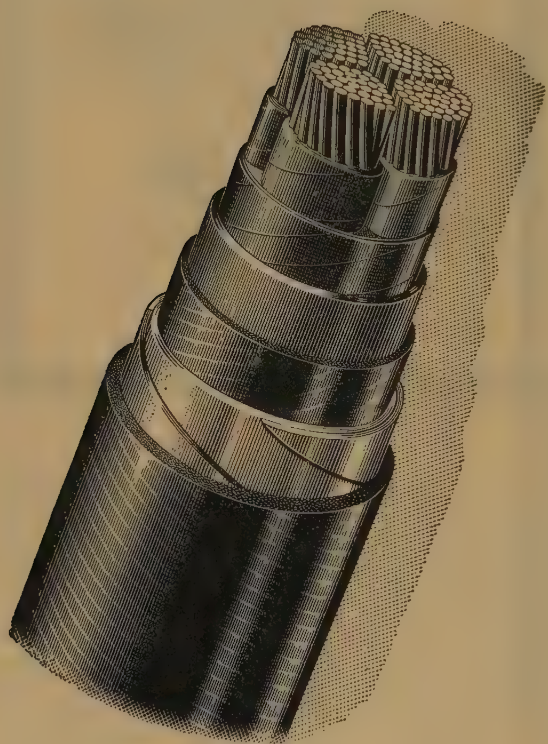

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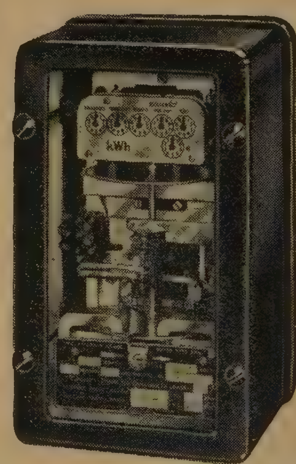

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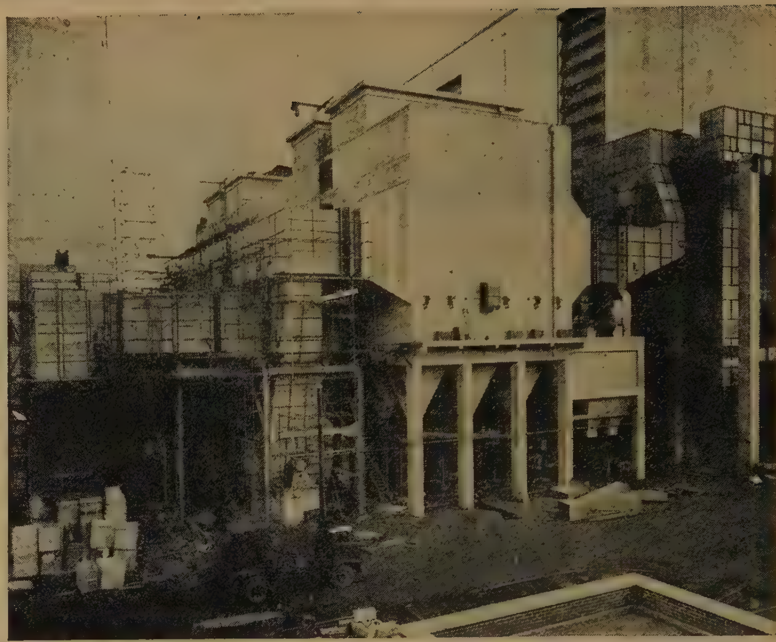

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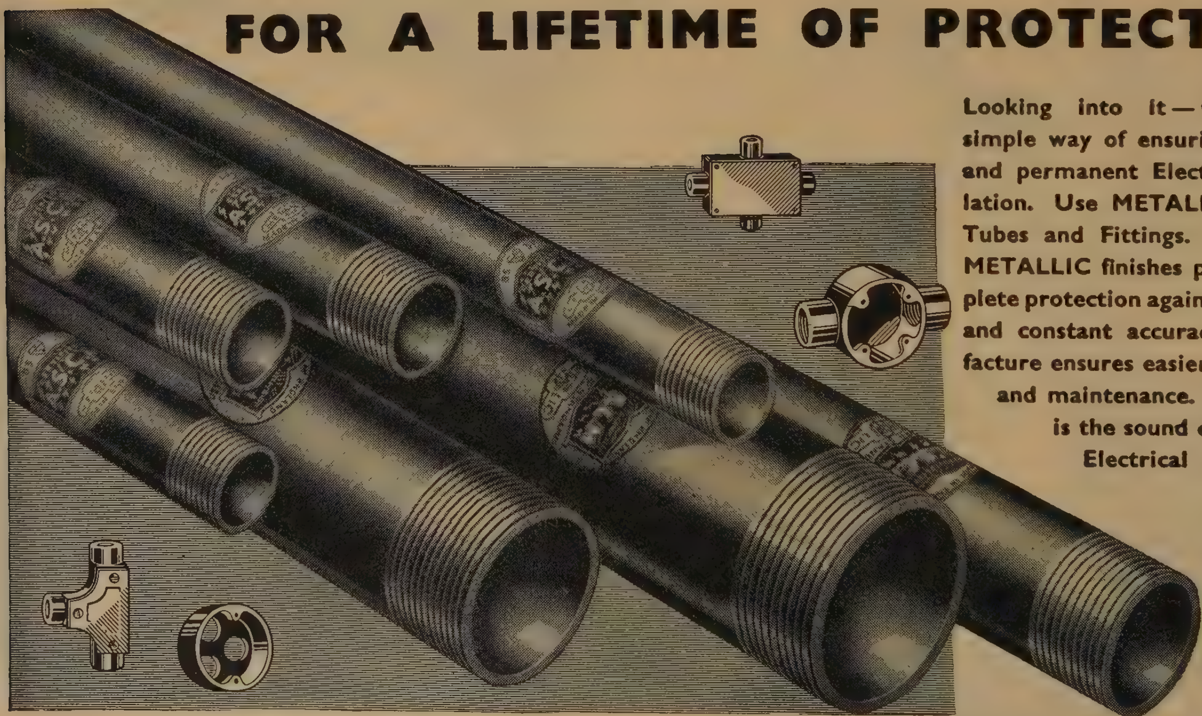

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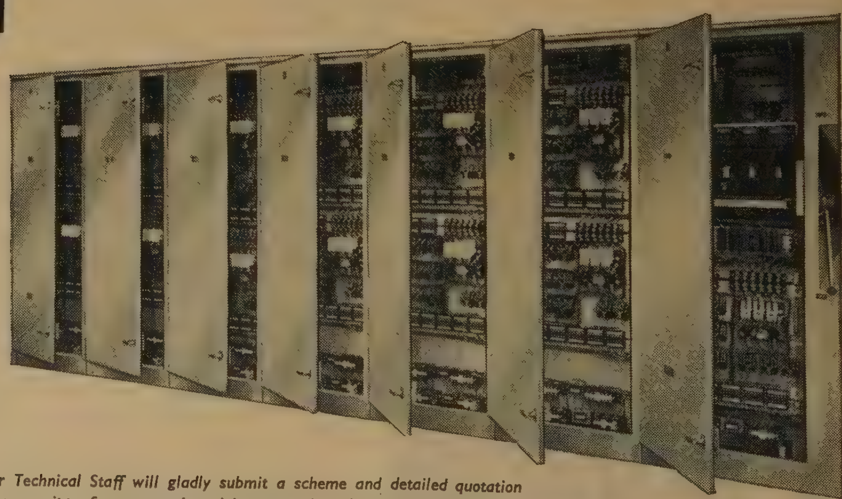

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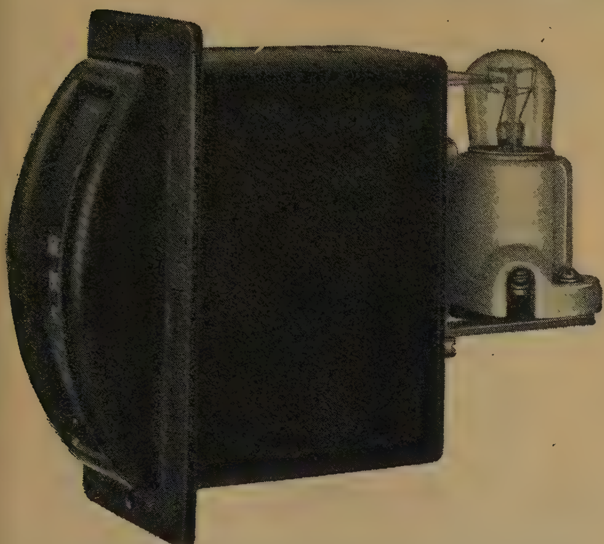

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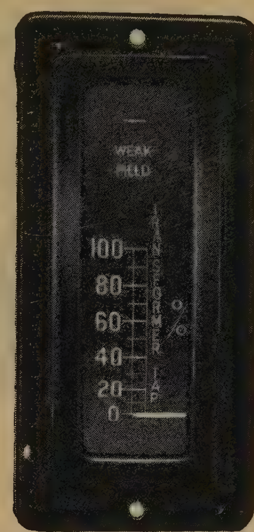

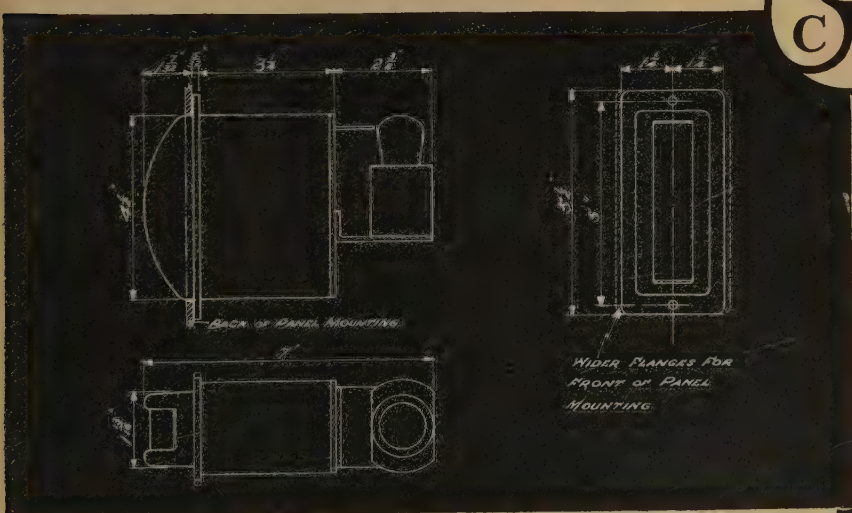

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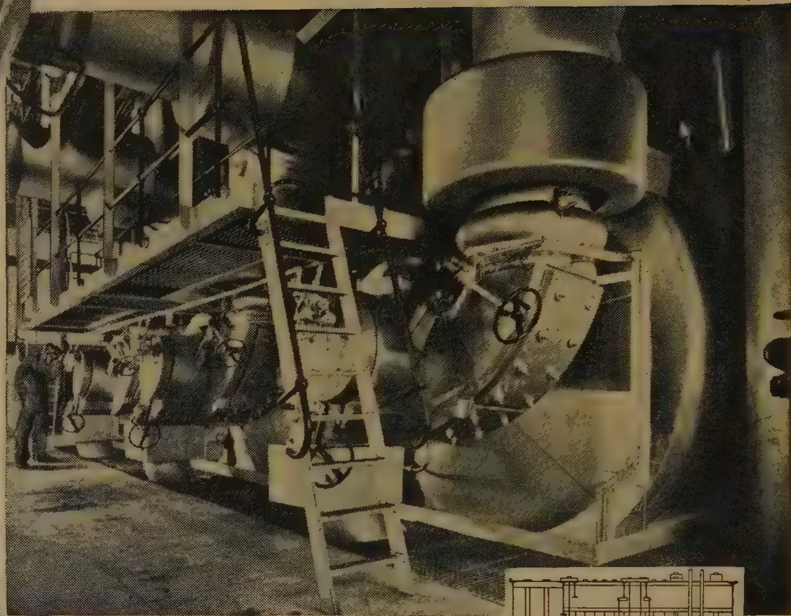

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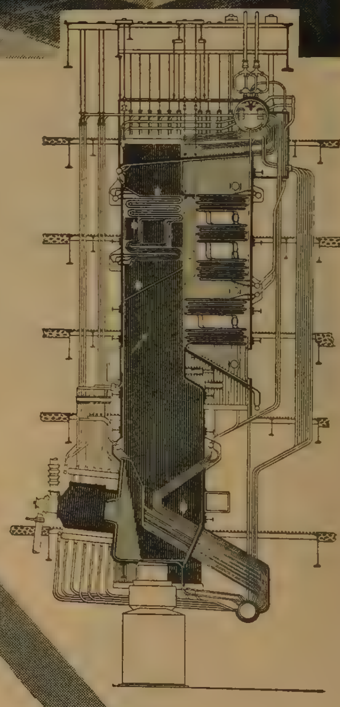

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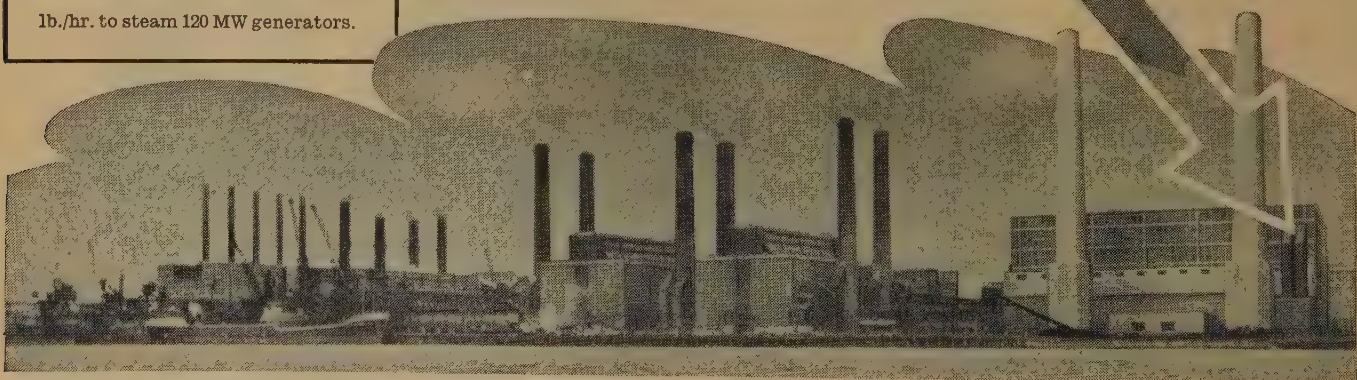

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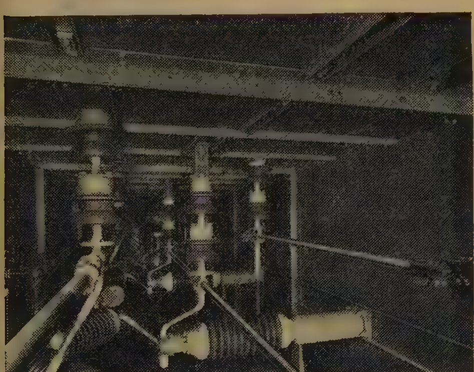
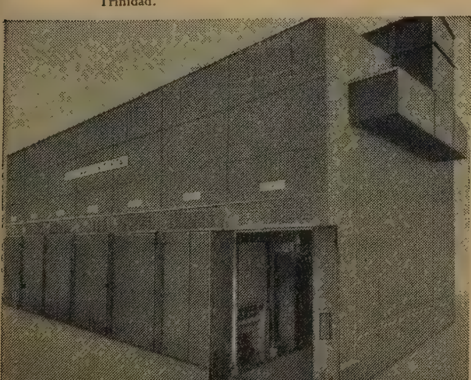
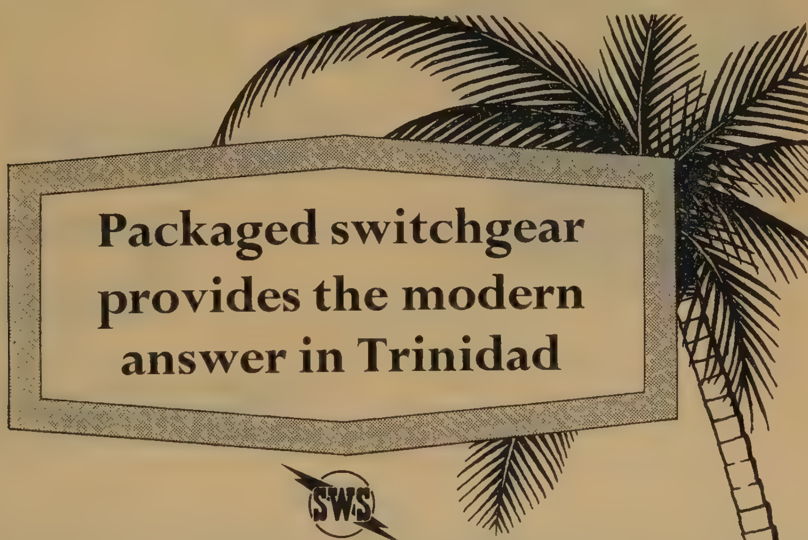


above: the busbar chamber of a 33kV type UEI switchboard.

below: a 7-panel duplicate busbar, air-insulated switchboard for 33kV, 1 000MVA, service, with motor wound spring operated mechanism, supplied to The Electricity Commission, Port of Spain, Trinidad.





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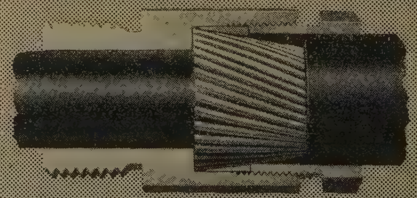

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A SLIDING-ROTOR INDUCTION MOTOR

By D. MIDGLEY, B.Sc., Ph.D.

(The paper was first received 23rd January, and in revised form 9th April, 1959.)

SUMMARY

A method of designing an induction motor to have continuously ariable speed is described. It involves a short sliding rotor and a ong stator, the poles of which are changed gradually over the length. 'ests on an experimental model are reported and the consequences of liscontinuities in the stator flux pattern are considered.

(1) INTRODUCTION

In recent years the goal of a practical variable-speed quirrel-cage motor has been pursued principally along two aths. Williams[1] and his associates have created machines vith continuously variable speed by exploiting principles of vave propagation, which are more usually encountered in trans-nission line and communication theory. Their designs are ometimes strikingly unconventional and lead to new problems f both theory and construction. Making a different approach, Rawcliffe[2] and one or two other workers have evolved ingenious econnections of the stator so as to vary the number or distri-ution of the poles. Large changes in running speed are uccessfully combined with a tried and tested conventional frame, ut the synchronous speed is not smoothly varied.

Some aspects of both these lines of thought are combined in e sliding-rotor machine. It could correctly be described as a ole-changing machine, but irregular distributions of the poles ccur at intervals; these are indeed examples of 'pole amplitude odulation'.[2] On the other hand, not machine theory, but deas transferred from wave and communication theory, have rovided the main interest and impetus. The quest has been or a continuously variable wave velocity, but this has not eveloped into another exploitation of the abnormally high hase velocities, which occur on an oblique cut through a lane wavefront.[1]

The investigation of the sliding-rotor machine has been onfined to essentials at present. For instance, particular ttention is not given to stator copper losses and efficiency, nce there is little reason to expect that established methods would fail to improve these. On the contrary, simplicity in construction has been the aim in building the prototype, the m.m.f. being supplied by a heavy current flowing in one turn. Consequently, experiments are concerned with speed/torque characteristics and with tests to reveal a gradual change in the apparent synchronous speed. Theoretical discussion is directed towards questions of graduated synchronous speed and the resolution of irregularities in the flux pattern into harmonics.

(2) PRINCIPLE

There is no difficulty in imagining a rolled out or linear induction motor to be modified for variable speed by graduated spacing of the poles. The stator represents a non-uniform transmission line, which propagates, in general, a wave with changing group velocity. If an observer on a fragment of the 'rotor' moved so as to remain in step with a wavefront, his motion would justifiably be described as synchronous. In order to return to cylindrical geometry without losing variable speed, let the non-uniform line be wound helically around a cylindrical rotor space, but let the axial length of the rotor be so reduced as to permit action with only one turn of the helix (Fig. 1). An

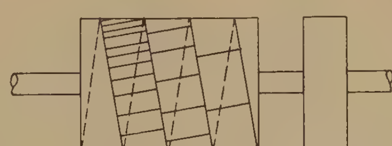

Fig. 1.—Helical-line stator.

observer on a fragment of the rotor may now remain in step with a wavefront only by combining axial and rotary motion. Such exact synchronous motion is denied to a complete rigid rotor, rotating steadily without translation; but, in practice, a steady running speed, roughly proportional to axial displace-ment, is clearly possible when a small degree of slip is allowed. This applies equally when the somewhat impractical helix is replaced by simpler methods of varying the wave velocity along the stator axis. A method of varying the pole pitch is chosen for the experimental machine.

Written contributions on papers published without being read at meetings are vited for consideration with a view to publication.
Dr. Midgley is Lecturer in Electrical Engineering, Queen's College, Dundee, niversity of St. Andrews.

) 1959: The Institution of Electrical Engineers

(3) EXPERIMENTAL MACHINE

The stator is a stack of ring stampings which differ from one another in the punching of the slots. In any one stamping the spacing between the slots is constant, the angular measure being θ_z, say (Fig. 2). One key punching at $\theta = 0$ is common to all

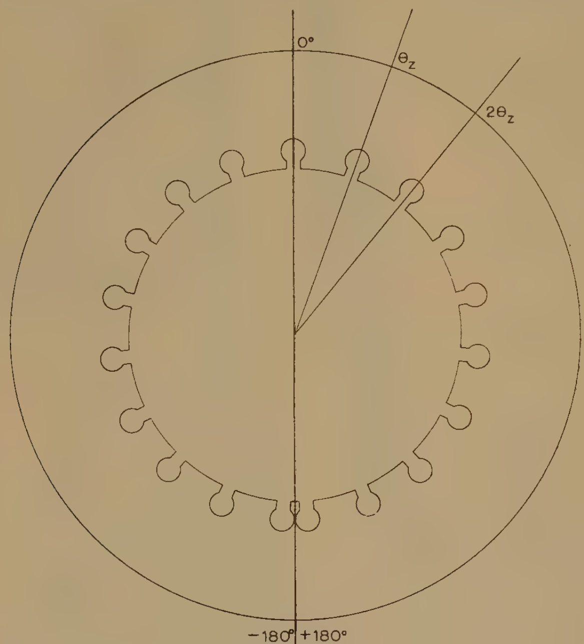

Fig. 2.—Typical stamping (half the actual number of slots).

the stampings in the sense that the completed slot lies parallel to the machine axis. The remaining punchings are measured from this one at $\theta = \pm\theta_z, \pm 2\theta_z, \ldots$ and so on until $\theta = \pm 180°$, where there is an irregularity if $180°/\theta_z$ is non-integral.

θ_z is varied slightly from one stamping to the next. In this instance, numbering the stampings from $z = 0$ to $z = 100$, the zth stamping has punchings spaced at the angle

$$\theta_z = 10 - \frac{z}{100} \text{ deg}$$

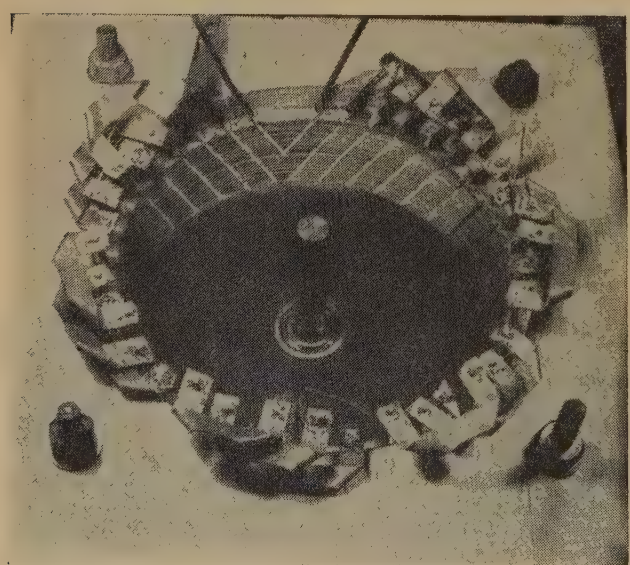

Fig. 3.—Experimental machine.

Thus the stator starts with 36 slots 10° apart and ends wit 40 slots at 9° (Fig. 3). Over this short length the slots are nearl straight, but, if the process were continued, they would be see as parts of helixes, each with a different pitch.

The nature of the stator is perhaps more clearly revealed b the rolled-out winding diagram (Fig. 4). This also shows th end-connections for a 3-phase 12-pole winding. Where tw slots run together, their conductors are, in fact, joined. Th suits only a few of the possible methods of making enc connections, and it would be better to bring out the individu conductors before union, through radial holes in the stator.

Principal Dimensions, etc.

Rotor diameters (solid and squirrel cage)	9 in
Rotor thicknesses	1 in
Air-gap	15 mils
Stator outer diameter	13 in
Stator length	2½ in
Slot width	⅛ in
Hole at base of slot	¼ in diameter o 4¾ in diamete
Conductors	Single ⅛ in copper rod
Number of slots	36–40
Number of stampings	101

(4) EXPERIMENTAL RESULTS

Numerous trials at various stator currents and with bot solid-iron and squirrel-cage rotors show that there is invariab a smooth change in speed of usually rather more than 10% a the rotor slides from one end of the stator to the other. This

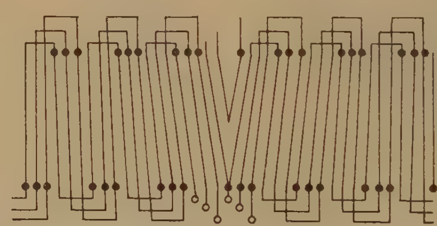

Fig. 4.—Rolled-out stator showing end-connections.

so even when the rotor conductors are equal in number to thos of the stator at one end. Such equality must arise somewhe over the long axis of a complete machine built for a wide spee range. The variation of no-load speed against axial position shown in Fig. 5, using a solid-iron rotor and a phase current 60 amp supplied at about 1 volt by 3-phase 50 c/s transformer

The synchronous-speed line comes from application of th usual relation for speed, pole pairs and frequency ($f = pn$ even when p is non-integral, in which case a value for p require division of the circumference by the pole pitch. The chang in running speed is predicted reasonably well by this, bu because there is always slip, experiment does not establish wi certainty that graduated changes in the synchronous speed exi in fact. The effect of increasing the stator current so as to clo the gap between running and synchronous speeds is shown Fig. 6.

Such tests end abruptly when side-pull on the rotor is allie with shaft whip and flexure in the bearing framework. How ever, the curves, which refer to the two extreme rotor position suggest that 450 and 500 r.p.m. are not unreasonable as asym totes to their extrapolations; 500 r.p.m. is a normal synchrono speed for six complete pole pairs using 36 slots, whereas 450 r.p.

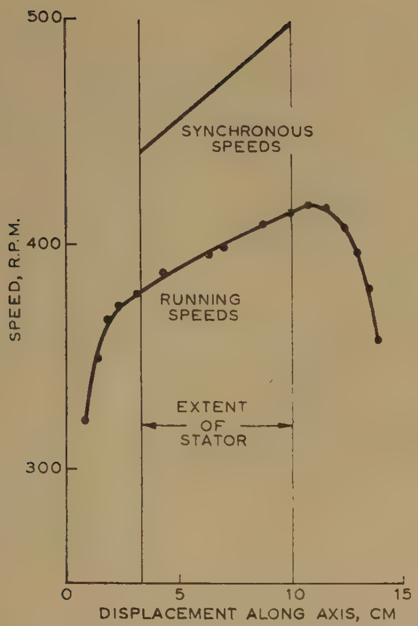

Fig. 5.—Variation of speed with axial displacement.

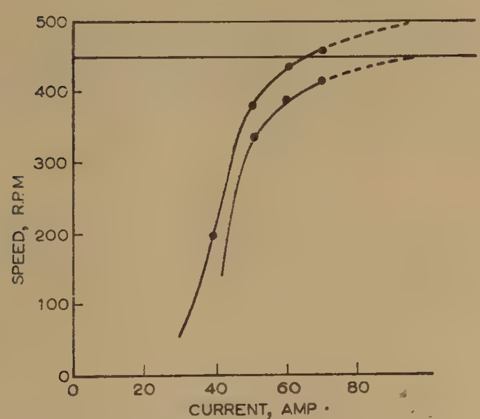

Fig. 6.—Variation of speed with stator current.

equires the $6\frac{2}{3}$ pole pairs that 40 slots provide. It is impossible o run with zero slip at 450 r.p.m. by having permanent magnetism or simple d.c. injection in the rotor, since a sudden change n the magnetic axis is required once per revolution.

Speed/torque curves are shown in Fig. 7 for the two extreme otor positions. These reaffirm the speeds at no load and show hat a better speed ratio accompanies sliding of the rotor against constant load torque. Apart from direct measurements of he standstill torques, the curves are deduced from records of cceleration tests. A pen record of revolutions against time is nade as the machine accelerates against the inertia of the rotor. Numerical differentiation gives the velocity and acceleration. The experiment is simple to perform and a convenient permanent ecord is made, but significant figures are lost during differentiaion and only a few points are deducible near the start. Against his, the final no-load speed is established with some certainty vith no shortage of results in that region. There are dips in he curves near full speed. These are tentatively attributed o flux harmonics, although mechanical resonances could be esponsible.

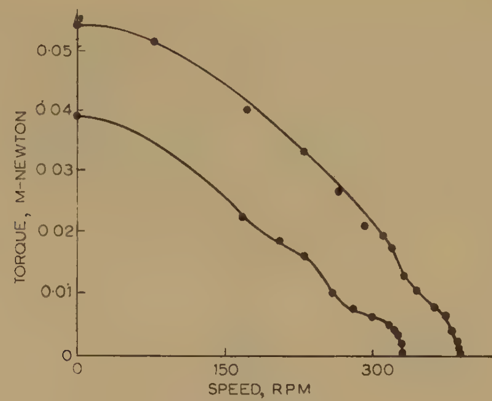

Fig. 7.—Speed/torque curves.

Torque, m–n	*Speed ratio*
0	1·18
0·01	1·35
0·02	1·61
0·03	2·10
0·035	3·04
0·04–0·05	∞

(5) FLUX HARMONICS AND GRADUATED SYNCHRONOUS SPEED

It may be objected that it is improper to introduce graduated synchronous speeds through extension of the $f = pn$ formula to non-integral p. Any flux pattern in a cylindrical machine is periodic and may be analysed into a series of sinusoidal distributions. At 50 c/s the first, second and third of these have synchronous speeds of 3 000, 1 500 and 1 000 r.p.m., etc., and these may be regarded as the only true synchronous speeds. This description seems right for most 3-phase windings in slots, because the stepped m.m.f. wave does not rotate intact, so as to preserve its shape at all instants.

But now consider a simpler hypothetical stator. Suppose that a hollow conducting cylinder is supplied with direct current by two contacts, one on each rim, one fixed and the other sliding steadily around the rim. A 2-pole m.m.f. wave is created by current flowing over the shortest curved path between the contacts. At the end with the sliding contact the m.m.f. pattern rotates at full speed around a full circle. At any other point along the axis, only an arc of the circle is covered by the m.m.f. wave in the same period, so that there is a reduced group velocity governed by axial position. The range of such shortest paths followed by currents in the surface of the cylinder is indicated in Fig. 8. Although the m.m.f. wave now preserves its shape

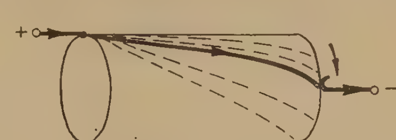

Fig. 8.—Cylinder with one fixed and one rotating brush.

during its motion, it could still be treated by decomposition into sinusoidal components with synchronous speeds in integral ratios, but the process would seem needlessly elaborate and artificial.

Moreover, no preference for sinusoids is to be expected of a solid rotor. It has currents to suit whatever flux pattern is applied, and, in seeking to reduce these to zero, it tries to move at a fractional or graduated synchronous speed, so as to match the group velocity of the whole m.m.f. wave. This is surely simpler than insisting after sinusoidal analysis that the rotor finds a speed where there is balance among the torques due to

positive and negative slips associated with multiple phase velocities. Harmonic analysis is, however, useful for a comparison of windings with and without irregularities.

Fig. 9 shows spectra for rolled-out m.m.f. distributions in one phase of the experimental machine. Two terms are distinguished in the expression for the amplitude of the nth harmonic, which is derived in an Appendix. The first has the form

$$\frac{\sin\left(\frac{\pi n d s}{T}\right)}{\pi n}$$

is known as a winding factor[3] and is determined by the shape of the individual pole. The second is the function

$$\frac{\sin\left(\frac{\pi n d s}{T}\right)}{\sin\left(\frac{\pi n d}{T}\right)}$$

a distribution factor,[3] which depends upon the number and disposition of the poles. These factors correspond to polar diagram and beaming factor in aerial theory.

Starting with six poles and no irregularity, the harmonics coincide with zero values of the distribution factor, except when $n = 0, 6, 12, 18 \ldots$. After multiplication by the winding factor, only the sixth, eighteenth . . . remain, being equivalent to first, third . . . and other odd harmonics of an analysis performed with the more usual minimum period. The former coincidences with zero are destroyed by a reduction in the pole size and pitch, and all the formerly absent harmonics appear, generally with small amplitudes. Exceptions are those harmonics which fall within the main lobes of the distribution factor, namely the sixth, seventh, twelfth, thirteenth, and fourteenth during the modification of a stator from six to seven pole pairs.

Moving down Fig. 9, there is a gradual transfer of dominance from the sixth to the seventh harmonic, and this is reflected in their multiples. For instance, when six pole pairs are fitted into a space for $6\frac{1}{2}$, the distribution factor gives equal weight to the sixth and seventh harmonics and the thirteenth appears at full strength. The fifth Figure shows the penalty in terms of unwanted harmonics for omitting the seventh pole pair, when there is room for it. Finally, the improvement in seventh harmonic is demonstrated in the last two Figures by the introduction of the extra pole pair at the earliest opportunity.

An appreciation of the problem of merging any number of pole pairs into an adjacent number is grasped by inspecting a family of $\sin nx/\sin x$ curves.[4] The introduction of one more pole pair into an already large number is easily accomplished, all harmonics being negligible except those lying under the main lobes and actively engaged in the transition. At the opposite extreme, in a transition from two to three pole pairs, the spectra would appear chaotic and one would expect practical operation of such a motor to be bedevilled by crawling, sharply-curved slots and losses due to grossly incomplete windings.

It is helpful to imagine that the machine could generate so as to reproduce the m.m.f. patterns as e.m.f. waveforms in time. The diagrams then become actual frequency spectra, which are limited as usual to the discrete harmonics of the fundamental. Despite this, they seem to strive to convey an impression of the graduated instantaneous frequencies, which are clearly apparent in the time domain. It may be observed that in the time domain the instantaneous phase is modulated by being reset once per revolution. This change of viewpoint leads to acceptance of graduated synchronous speed as a concept with validity equal to that of instantaneous frequency.

Fig. 9.—Harmonic analyses of m.m.f. distributions.

(6) CONCLUSION

Some preliminary tests on an experimental machine have monstrated the feasibility of sliding the rotor to secure gradual riation in the speed of an induction motor. The need for an travagantly long frame is the most important obstacle to dustrial exploitation of a machine with a good speed ratio, it the cost, size and weight of the idle iron in such a stator ay not be too objectionable in certain applications. Copper sses in the idle parts of the stator are avoidable by arranging nnectors to slide with the rotor and energize only the relevant action of the stator.

It is impossible at present to be certain of the efficiency of a ding-rotor machine, but reasonable efficiencies are to be pected of a less primitive model with multi-turn coils and a gher input voltage, because, in essence, the machine closely sembles a normal motor. The skew in the stator slots is hardly ore than is normally given to rotor slots to avoid crawling, id there are no large gaps in the stator winding, provided that e smallest numbers of pole pairs are avoided.

Study of the stator-flux harmonics shows that graduated ole changing is most suited to slow machines with many pole iirs. In this connection it is argued that the description of .m.f. waves in terms of sinusoidal components with discrete eeds is not unique and that graduated synchronous speed is a ilid and useful alternative concept.

(7) ACKNOWLEDGMENT

For interest taken, advice and assistance given the author is ateful to Professor E. G. Cullwick and colleagues at the niversity of St. Andrews, and particularly to Mr. W. R. IcEwan, who took charge of the construction of the stator id performed a large number of calculations to enable him to iark out by hand the position of every slot.

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(9) APPENDIX: FOURIER ANALYSIS OF THE M.M.F. WAVE

The Laplace transform of the waveform (Fig. 10) is taken; then, ter rearrangement of terms, the inverse transform gives the

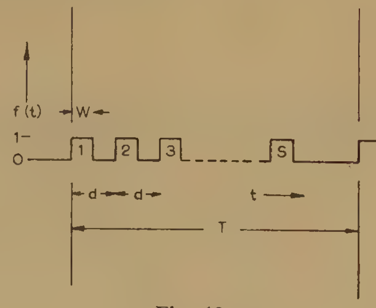

Fig. 10

original function as a Fourier series.[5] Other methods may be simpler in principle, but they sometimes seem laborious and out of touch with the essentials of the problem.

Let $F(p)$ be the transform of the whole function $f(t)$, and $F_T(p)$ be the transform of the first period of $f(t)$. Since the transform of the upward step at the origin is $1/p$ and that of the downward step after time w is $-\varepsilon^{wp}/p$, $F_T(p)$ may be written

$$F_T(p) = \frac{1}{p}(1 - \varepsilon^{-wp}) + \frac{1}{p}\varepsilon^{-dp}(1 - \varepsilon^{-wp}) + \ldots + \frac{1}{p}\varepsilon^{-dsp}(1 - \varepsilon^{-wp})$$

$$= \frac{1}{p}(1 - \varepsilon^{-wp})\frac{(1 - \varepsilon^{-pds})}{(1 - \varepsilon^{-pd})}$$

by summing the finite geometrical series.

Since $F(p)$ is $F_T(p)$ repeated in the time domain indefinitely at intervals of T, one may write

$$F(p) = F_T(p)\,(1 + \varepsilon^{-Tp} + \varepsilon^{-2Tp} + \ldots)$$

$$= \frac{F_T(p)}{1 - \varepsilon^{-Tp}}$$

Substituting the equation for $F_T(p)$,

$$F(p) = \frac{1}{p}\,\frac{1 - \varepsilon^{-wp}}{1 - \varepsilon^{-Tp}}\,\frac{1 - \varepsilon^{-pds}}{1 - \varepsilon^{-pd}}$$

Summing the residues at the poles $p = j2\pi n/T$, where n is integral, and converting the remaining $1 - \varepsilon^{-jx}$ terms to sine equivalents, one has

$$f(t) = (a_0) + \sum_{n=-\infty}^{\infty} \frac{\sin\left(\frac{\pi n w}{T}\right)}{\pi n}\,\frac{\sin\left(\frac{\pi n d s}{T}\right)}{\sin\left(\frac{\pi n d}{T}\right)} \times \exp\left[\frac{j2\pi n t}{T} - \frac{j\pi n}{T}(w + ds - d)\right]$$

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THE INFLUENCE OF CONSUMERS' LOAD/CONSUMPTION CHARACTERISTICS ON METERING PRACTICE

By L. B. S. GOLDS, Member.

(*The paper was first received 7th November*, 1958, *and in revised form 6th January*, 1959. *It was published in February*, 1959, *and was read before the* MEASUREMENT AND CONTROL SECTION *3rd March*, 1959.)

SUMMARY

The paper presents the results of further investigations, carried out under the aegis of the Utilization Research Committee of the former Central Electricity Authority and Area Boards, into the load/consumption characteristics of domestic consumers' installations. These are combined with the results of the pilot tests giving over 400 sets of data, and their influence upon the performance, utilization and design of integrating meters is discussed. A system of weighting the errors found in 'off-service' sample meter tests at certain load currents is proposed in order to arrive at the error of total energy measured, and a formula is given for the economic service period. Suggestions are made for the setting of a recertification period by reference to the statistical distribution of meter 'weighted' errors as determined by sample tests at specified load currents. A possible revision of the standard ratings of meters is discussed, and proposals are made for the better utilization of existing meters to achieve maximum service and recertification periods.

(1) INTRODUCTION

The term load factor is defined in B.S. 205: 1943 as

$$\frac{\text{Consumption}}{\text{Maximum demand} \times \text{Time}}$$

For most purposes this term gives a sufficiently clear indication of the utilization of any electrical apparatus, i.e. it gives an indication of the utilization of the supply within a load range, the upper limit of which is the maximum demand. It does not, however, indicate whether the supply has been taken for a long time at low load or a short time at high load. For many purposes it is not necessary to know this, but in order to be able to gauge the overall performance of an integrating meter it is essential to ascertain the consumption at various levels of load for certain specific classes of consumer. Therefore it is necessary to determine the characteristics of the individual consumers' load/consumption. To obtain this information a load analysing meter was developed by the author, and a pilot test employing the meter was described in Reference 1.[1] The present paper, which is in the nature of a sequel, sets down and discusses the results of further tests and investigations in various parts of the country combined with those in the pilot tests and the influence of these results upon the performance, utilization and design of integrating meters.

The electrical-energy consumption of all domestic premises in the Electricity Board areas of England and Wales[2] in the financial year ending 31st March, 1958, was 22 108 143 MWh, which, translated into terms of money, provided a revenue of £154 126 824. This, together with the fact that the annual domestic-meter maintenance cost approximated to £1 500 000, emphasizes the importance of the technical and economic problems of measurement of supplies of electricity from the points of view of the supply industry and the consumers themselves.

Mr. Golds is with the Eastern Electricity Board.

(2) INVESTIGATION RESULTS

The tests and investigations were made in four territories, A, B, C and D, situated in parts of the country with differing consumers' load characteristics.

Including the pilot investigation A described in the earlier paper, the combined results of the investigation now cover more than 400 domestic consumers selected at random from each of the four representative areas.

As pointed out in the previous paper it was realized at an early stage that the investigation was an operational-research problem, and responsibility for its conduct was therefore assumed by the Utilization Research Committee of the former Central Electricity Authority and Area Boards.

(2.1) Characteristics of the Samples

The characteristics of the samples are given in Table 1.

The Table is important as the statistics have a profound effect upon the results obtained in each of the tests. A study of the figures enables the results of an investigation in other territories in the country with similar statistics to be assessed. Furthermore, it enables one to judge the changes likely to occur in the consumer's load characteristics due to future increase in installed loads of the types specified, in territories having rather less development than those in the samples. The method of selecting the samples was described in detail in the earlier paper.

(2.2) Load/Consumption Analysis

In the load-analysing meter employed in the tests[3] the energy is integrated on four separate registers, which give (*a*) the consumption when the load does not exceed 10%, (*b*) when it is within 10–25%, (*c*) 25–100% and (*d*) when it is over 100% of the meter rating. In samples A, B and C the short- or long-range load-analysing meter rating was matched to that of the existing meter and the values of the sub-ranges were similar in each case. For sample D the maximum continuous rating of the load-analysing meter was matched approximately to the installed load. This was done to ascertain the effect on the distribution of the consumption over the sub-ranges of installing meters on the basis of Table 2.

In order to investigate the effect of adopting an intermediate meter rating of 20 amp m.c.r., the load-analysing meters connected to installations having installed loads between 15 and 30 amp had the rating of the analysing meters changed on alternate months from 40 to 20 amp. The annual consumptions in the sub-ranges were therefore twice those actually recorded.

Table 3 gives the results and the average of the four tests. It must be emphasized that the two sets of figures for sample D are based not on the actual service-meter rating but on maximum continuous ratings chosen in accordance with Table 2.

The significance of the results shown in Table 3 is considered in Section 3. However, it is interesting to note that the effect on the consumption in the under 5% sub-range of introducing an intermediate rating of 20 amp m.c.r. between 10 and 40 amp m.c.r. is small compared with the omission in sample B of a

Table 1

CHARACTERISTICS OF SAMPLES

Sample	A	B	C	D	National survey
(*a*) *Period of Test*	Nov., 1950 to Oct., 1951	June, 1952 to May, 1953	May, 1954 to Apr., 1955	May, 1954 to Apr., 1955	1955
(*b*) *Consumers in Territory Sampled*					
Number of domestic consumers in territory	400 000	37 000	44 000	265 000	
Saturation factors					
Cooking, %	22	19	56	21	24·5
Water-heating, %	11	28	7	13	20·6
Space-heating, %	81	78	60	67	60·5
Average installed load (approx.) kW	5·6	4·9	7·6	3·9	5·2
Space-heating (approx.), kW	2·3	1·5	1·4	1·2	1·4
Average annual consumption in territory, kWh	2 250	1 230	2 255	1 450	1 540
(*c*) *House-Service Meters*					
Number in sample	110	110	110	110	
Average period since manufacture, years	14	10	10	13	
Average period since last calibration, years	10·5	6·5	8·2	5·1	

(*d*) *Meter Size Distribution* Rating, amp	2·5	5	10	20	25	40	50
Sample A, %	—	33	22	33	9	1	2
Sample B, %	—	—	48	15	37	—	—
Sample C, %	—	14	26	6	51	2	1
Sample D, %	2	7	28	7	48	6	2

The rating quoted is the nameplate rating and may refer either to short range or long range

amp long-range service-meter rating when the consumption in e under 10% sub-range is 25% compared with approximately 4% in the other samples. While increased annual consumption sample B will probably reduce the percentage consumption the under 10% sub-range, such an increase would have to pproach 100% in order to make the percentage in the under)% sub-range comparable with that of the other samples. It hould also be noted that the sample D figures give the perentage consumption under 5%, between 5 and 12·5%, between 2·5 and 50% and over 50% m.c.r.

(2.3) Maximum Demands and Installed Loads

With the object of obtaining an indication of the maximum ad of each installation, and as an indication of the amount by hich the 'over 100%' range (or 'over 50%' m.c.r. in sample D) ad been exceeded, a thermal maximum-demand ammeter was installed with each load-analysing meter. Its use has yielded important data.

Figs. 1(*a*), (*b*), (*c*), (*d*) and (*e*) give the cumulative percentage of consumers with maximum demands, during a year, not exceeding the maximum demands shown for the four samples, respectively, and for the four samples combined. The approximate installed load is also shown in each Figure to illustrate the variation in diversity with increase in installed load, which should be carefully noted.

Table 2

Installed load	Maximum continuous rating of load-analysing meter
amp	amp
Up to 15	10
Over 15	40

Table 3

ANALYSIS OF ANNUAL CONSUMPTION BY LOAD SUB-RANGES

Load sub-range		Proportion of consumption											
		Sample A		Sample B		Sample C		Sample D				Average of all samples	
								10/40 amp		10/20/40 amp			
Long or short range	M.C.R. (sample D)	Proportion	Average per consumer	Proportion	Average per consumer	Proportion	Average per consumer	Proportion	Average per consumer	Proportion	Average per consumer	Proportion	Average per consumer
%	%	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh	%	kWh
Under 10	Under 5	13	288	25	319	14	322	16	238	14	201	16	274
10–25	5–12·5	23	527	16	198	13	281	27	403	25	358	21	353
25–100	12·5–50	56	1 285	48	597	50	1 133	53	770	48	705	51	898
Over 100	Over 50	8	187	11	137	23	520	4	63	13	190	12	219
		100	2 287	100	1 251	100	2 256	100	1 474	100	1 454	100	1 744

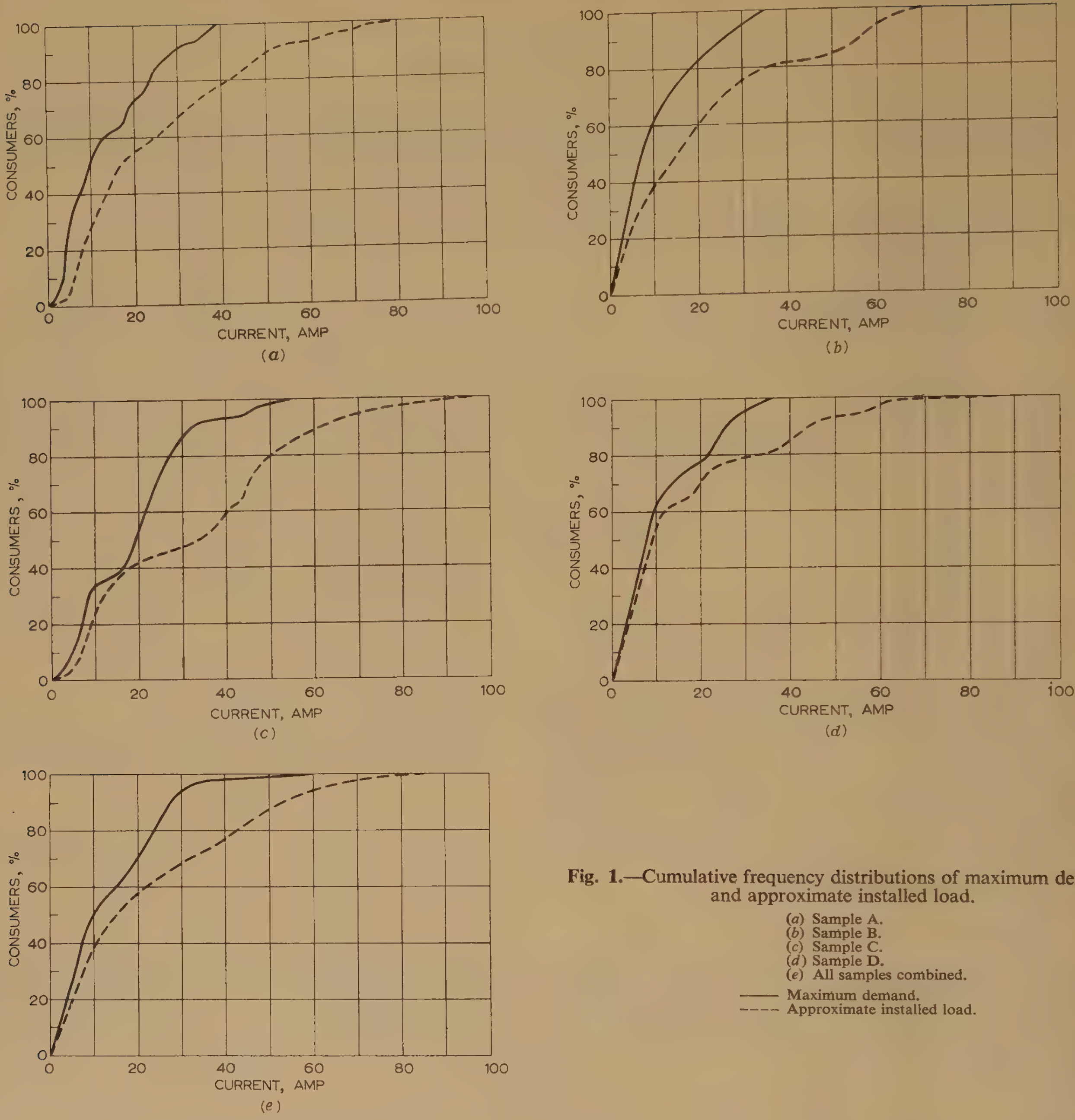


Fig. 1.—Cumulative frequency distributions of maximum demand and approximate installed load.

(a) Sample A.
(b) Sample B.
(c) Sample C.
(d) Sample D.
(e) All samples combined.

——— Maximum demand.
- - - - Approximate installed load.

(2.4) Annual Consumptions

Figs. 2(*a*), (*b*), (*c*), (*d*) and (*e*) show the cumulative percentage of consumers with annual consumptions not exceeding the values shown for the four samples, respectively, and for the four samples combined. It is striking that, in each sample, there is such a large percentage of the consumers with small consumptions. Reference is made to this in Sections 4 and 5.

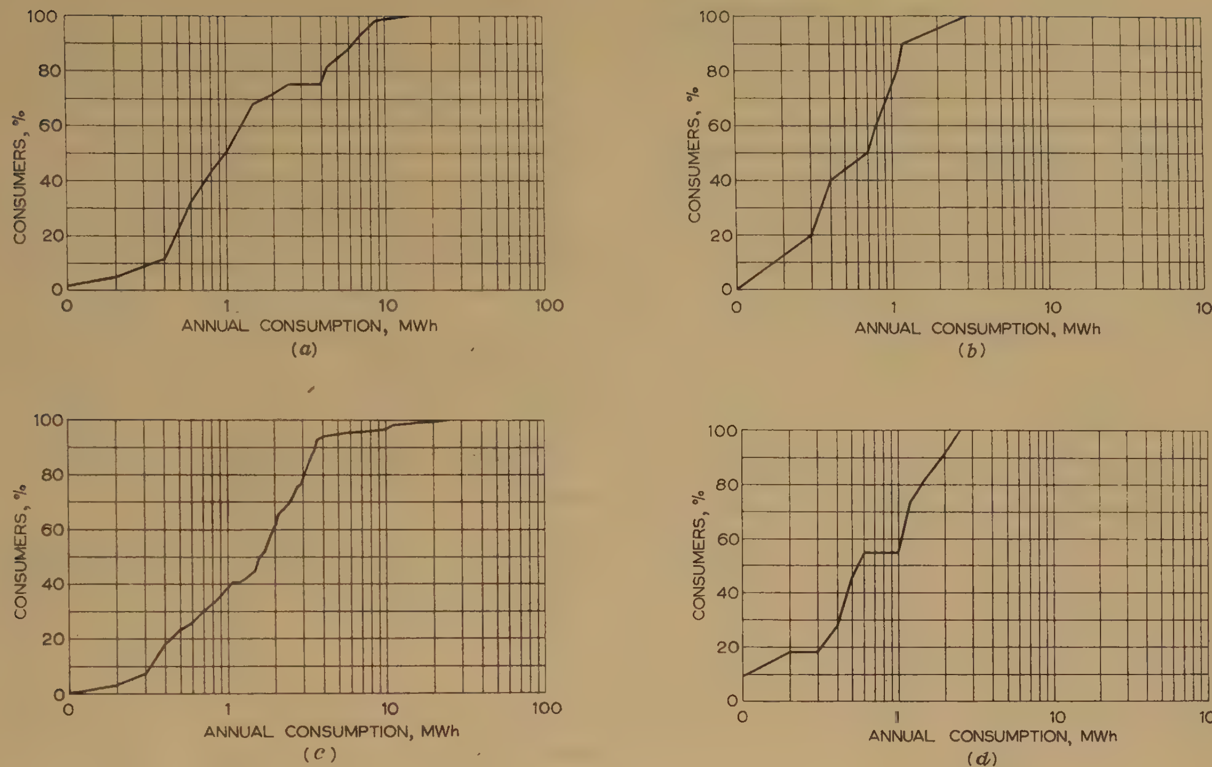
(2.5) Errors of Service Meters and Effect of Transportation

As stated in the Introduction, the primary purpose of the investigations into the proportion of the consumption between certain loads was to provide a means of assessing the error of total energy measurement of meters. It is therefore useful to know the errors of the service meters in the installations which were tested, together with the period during which they had been in service. As meter errors can be affected *inter alia* by transportation, a procedure was adopted to ascertain the error of the meter *in situ*, and again after careful transport to a meter testing station.

This procedure was not, however, adopted for sample A, where tests were taken only in the meter testing station after careful transport. The effect of movement of the meters in the other samples may be clearly seen from Table 4.

Individually, meters may have quite large removal errors, both fast and slow; this is shown in Table 4 for the meters in samples B, C and D. Allowance can be made statistically for the average removal error in order to obtain the average meter error *in situ*. The effect of the removal on the total registration is small since only 16% of the energy is registered at low loads on average.

The histograms of Fig. 3 show the distribution of the errors of the service meters in the tests. These were obtained after



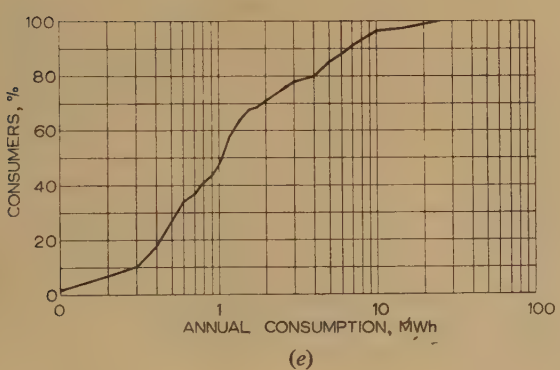


Fig. 2.—Cumulative frequency distributions of consumers' annual consumptions.

(a) Sample A.
(b) Sample B.
(c) Sample C.
(d) Sample D.
(e) All samples combined.

the meters had been carefully transported to the testing station and tested under similar electrical conditions at the conclusion of the investigation. The histograms for samples B, C and D are given for 5, 25, and 100% load, together with the average error in each case, whilst the loads for sample A are 5, 20 and 100%. The average period for which the meters have been in service is also indicated in Table 1. Although the errors are not necessarily normally distributed, owing to the mixture of types, makes and years of service in each case, there is a definite minus error trend indicated. This increases with service life, particularly at low loads on the meter. It is checked by comparing the actual registration of the service meters against the total registration of the load-analysing meters, which, although not precision grade, are, when taken as a batch, sufficiently accurate to compare the performance of the service meters. The difference between the actual registration of the service meters and the load-analysing meters are, for sample A, 0·2% low, for sample B, 1·1% low, for sample C, 0·8% low and for sample D, 0·1% low.

Taking the statutory limits of +2·5% and −3·5%, Fig. 3

Table 4

AVERAGE ERRORS MEASURED BEFORE AND AFTER REMOVAL

Test load	Average error		Effect of removal
	On site	Test bench	
1	2	3	4
%	%	%	%
(a) *Sample A*			
5	Figures not taken	−0·2	—
20		+0·3	—
100		+0·5	—
(b) *Sample B*			
5	−2·8*	−1·9*	+0·9*
25	−1·1*	−0·9*	+0·2
100	−0·5*	−0·2	+0·3
(c) *Sample C*			
5	−3·1	−3·6	−0·5
25	−1·5	−1·3	+0·2
100	−0·6	−0·5	+0·1
(d) *Sample D*			
5	−3·2	−1·7	+1·5
25	−1·1	−0·4	+0·7
100	−0·2	+0·1	+0·3
(e) *Samples B, C and D combined*			
5	−3·0	−2·4	+0·6
25	−1·3	−0·9	+0·4
100	−0·4	−0·2	+0·2

* Statistically significant (P = 0·95).

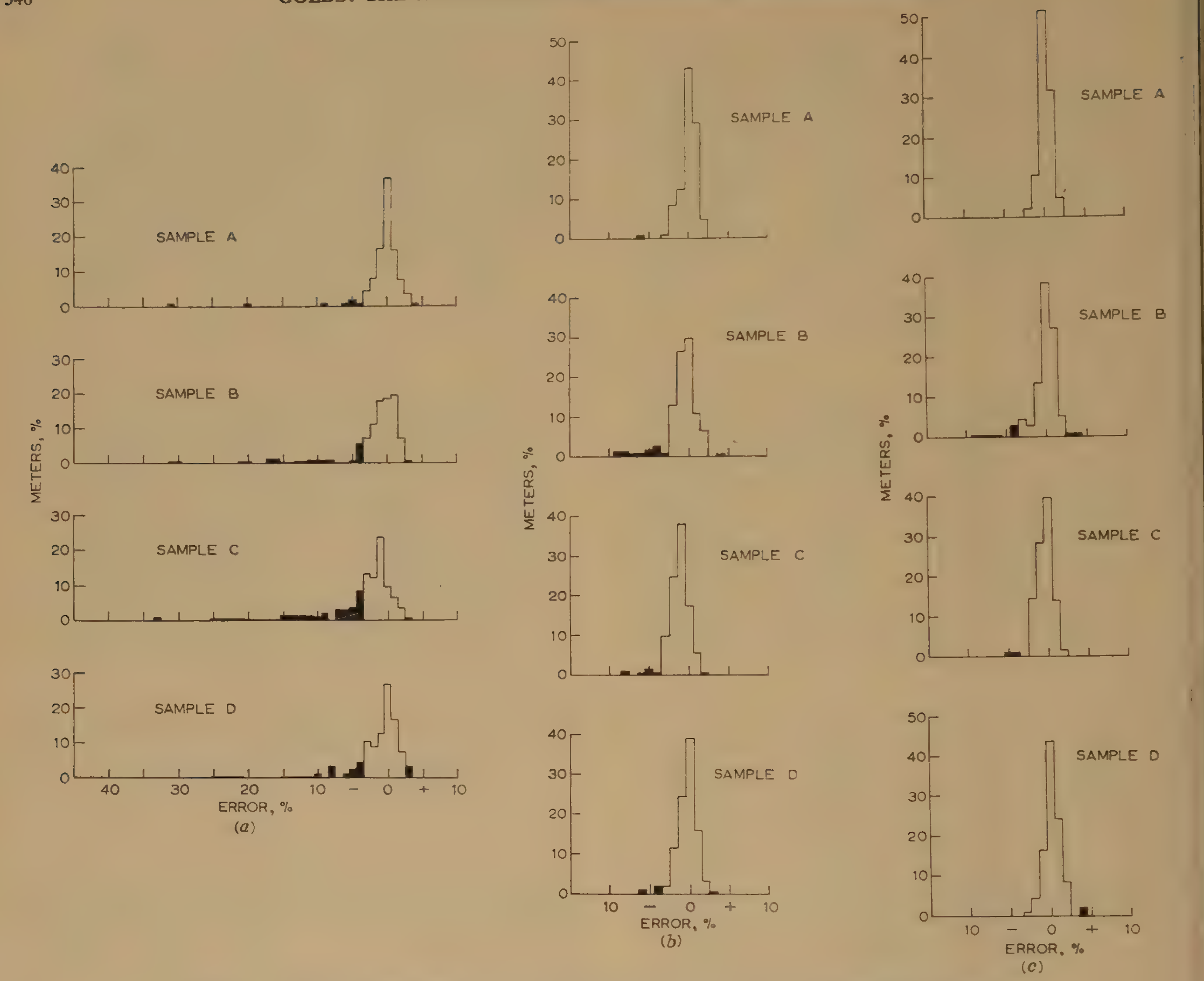


Fig. 3.—Frequency distribution of errors of service meters after removal at different load currents.

(a) 5%
(b) 25% (20% sample A)
(c) 100%

■ Meters outside statutory limits.
□ Meters within statutory limits.

shows the percentage of meters registering outside the limits in the four samples at 5, 20 or 25 and 100% loads.

(2.6) Distribution of Percentage Consumption over Lowest Load Sub-Range

While Table 3 gives the average consumption over the load sub-ranges, a detailed examination of the individual consumer's test results (Fig. 4) shows the cumulative percentage of the individual consumptions for samples A, B, C and D, where the load is under 10%, or under 5% m.c.r. in the case of sample D. The influence of the preponderance of low annual consumptions is clearly shown.

Between the early 1930's and 1952, meter manufacturers produced meters capable of measuring energy with reasonable accuracy up to about three times the marked current rating. Fig. 5 shows the small extent to which advantage of this improvement in design has (up to the time of the tests) been taken. Although there are rare cases where nearly 100% of the consumption has been measured on the 'overload' portion of the meter range, it will be apparent that there is ample scope for increased utilization of the supply without necessarily changing the existing installed meter ratings.

(2.7) Maximum Demands

From the readings of the demand ammeters it would appear that, owing to diversity of use of apparatus referred to in Section 2.3, the maximum sustained current taken by domestic consumers on standard 240-volt single-phase supplies is not likely much to exceed 50 amp. Although there will be peaks of higher values lasting for fractions of an hour, owing to the small percentage of the consumption during these times, the effect of under-registration at such currents cannot affect the total energy-measurement error of the meter appreciably. Generally, the short-period current-carrying capacity of the meter is not in question.

(2.8) Maximum Demand and Annual Consumption

Fig. 6 shows a scatter diagram of maximum demands plotted against annual consumptions for all the consumers in the investigation. Although this indicates that the load factors for

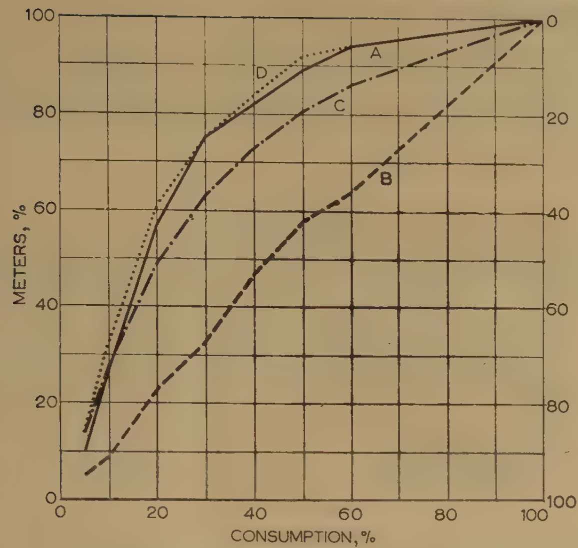


Fig. 4.—Cumulative frequency distribution of percentage of annual consumption within 0–10% load current sub-range.

——— Sample A. —·— Sample C.
– – – – Sample B. ····· Sample D.

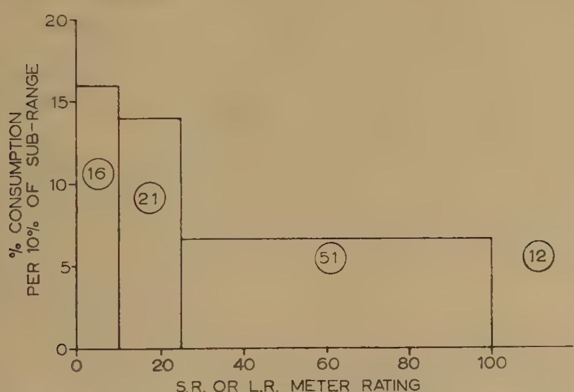


Fig. 5.—Load/consumption characteristics for the combined samples A, B, C and D.

the small annual consumptions vary widely, it is nevertheless possible to see a definite pattern, which will be referred to in Section 5.

(2.9) Load/Consumption Characteristics

While the investigations have provided useful data regarding the present utilization of the measuring range of the meters in

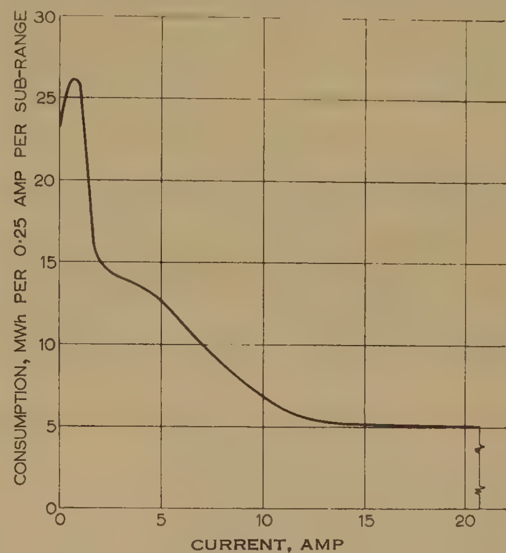


Fig. 7.—Consolidated load/consumption curve showing the consumption within the given 0·25 amp sub-range for all samples combined.

the territories concerned, still more important data may be deduced relating to the load currents at which the actual consumption takes place. For reasons given in the earlier paper, owing to the coarseness of load subdivision of the load-analysing meters, common current change-over points are not available for each rating of meter. However, a stepped diagram has been constructed for the combined investigations on the basis of kWh/per 0·25 amp for each sub-range, which results in Fig. 7 showing the consumption within any 0·25 amp within the load-current sub-range for the combined investigations. Fig. 8

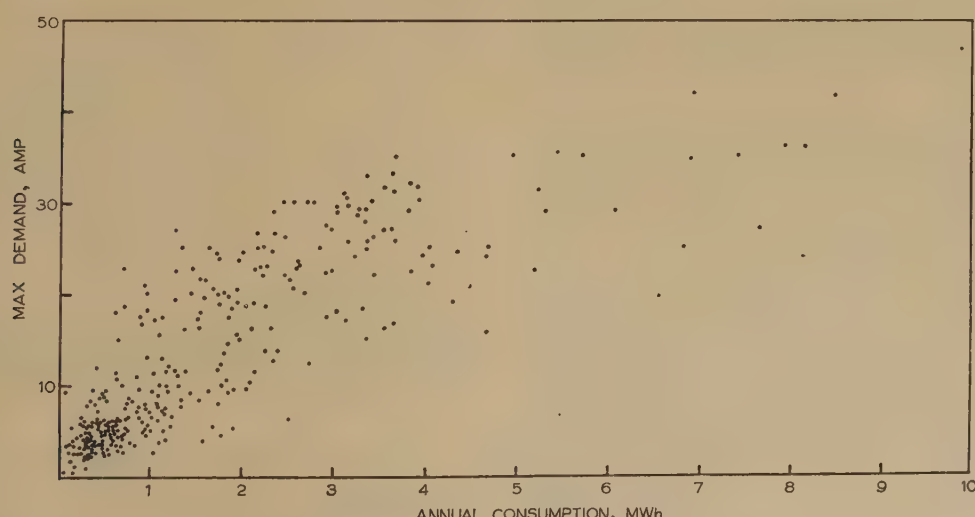


Fig. 6.—Scatter diagram of annual consumption related to maximum demand of individual consumers.

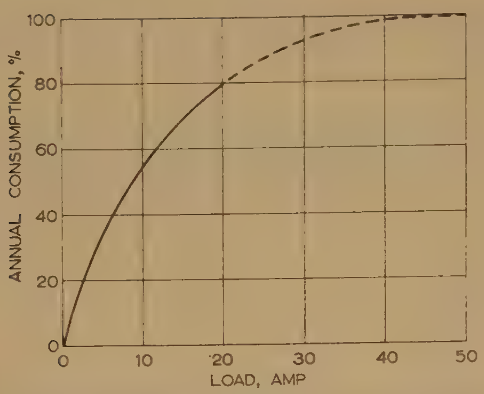


Fig. 8.—Cumulative load/consumption curve for all samples combined.

shows the cumulative percentage distribution of the load/consumption curve, and indicates that 54% of the consumption takes place at currents below 10 amp, i.e. within the measuring range of a 5 amp long-range meter, or a 10 amp m.c.r. meter, while 80% of the consumption takes place below 20 amp.

(3) SOME APPLICATIONS OF THE RESULTS OF THE INVESTIGATION

(3.1) General

Having ascertained the load currents at which the consumption should be measured with the least error over a period of years, one is led to apply the knowledge and to consider how the measurement may be made at the least cost, having particular regard for the statutory, technical and economic aspects.

(3.2) Statutory Aspects

Statutory tolerances for the measurement of electrical-energy consumption have long been applied. Those at present in force were made by Order in 1937 by which the consumers' consumption must be measured within a tolerance band of 2½% high and 3½% low. This tolerance band is enforced by the process of meter certification, and, in addition, the consumer has the right to demand a test at any time by a meter examiner. The tolerances apply to the total energy measurement of each meter and not to the error at some specific load current, although this is not stated categorically in the Order. The tolerance band applies to the smallest consumption in the domestic category as well as to the largest, whether or not the tolerances are economically justified for the smallest or vice versa. Furthermore the tolerance band is not symmetrical about zero, but is biased 0·5% on the low side.

Some meter errors are time-related, and, as forecast when the previous paper was presented, 'limitation of the period of validity of certification' is to be introduced by the responsible Minister. The aspects presented in this Section and in Section 3.6 may be of assistance in arriving at practical periods from the consumers' and supply industry viewpoints.

Since the consumers, in general, pay for the whole cost of electricity supply, the withdrawal of meters for recertification after a service period, which unnecessarily increases the cost, is not in their interest. Clearly, there will always be a risk of the percentage error in registration of the total energy exceeding the statutory tolerances, although it will probably be on the low side. That risk may be calculated and the approximate value of the energy likely to be registered inaccurately balanced against the cost of returning* all the meters periodically for servicing and recertification. The histograms in Figs. 3(*a*), (*b*), (*c*) and (*d*) show that the risk is approximately 5 times greater when the majority of the load is measured at 5% rather than at around 25% of the meter current rating. This underlines the importance of meter quality and servicing. Detailed consideration is given to this aspect in Section 3.6.

(3.3) Economics

Following publication of Reference 1, the economics of metering has been given a good deal of attention in Canada[4] and also continued in this country. It has been shown that the point in time at which it is economic to service a meter is when the integrated net loss of revenue is equal to the cost of one whole maintenance operation. This relation is fundamental and may be applied, not only to ascertaining the undertaking's economic maintenance period, but also, in a modified form, to the statutory recertification period.

The economic factors affecting the metering of electrical energy are as follows:

(*a*) The capital cost of the meter.
(*b*) The annual interest and depreciation charge on the meter.
(*c*) The annual metered revenue.
(*d*) The annual cost of maintaining the meter.
(*e*) The quality of the meter.

Labour and material costs, as well as complex commercial forces, largely control the capital cost of the meter. The annual interest and depreciation charges on the capital must be accepted as they stand for the purpose of this discussion. On the other hand, the Electricity Boards may, by exercising skill and initiative, have some control over the cost of maintenance, the quality of the meter and hence the metered revenue.

The costs of maintenance can be divided into direct and overhead charges. Direct charges include removal and replacement of meters at the consumers' premises, transport, clerical work involved in the change of meter, labour for handling, repair, recalibration, final testing and recording of tests, spare parts used in the repair, standardizing of test apparatus and certification. The overhead charges comprise annual charges on cost of buildings, meter stocks, heat, light and power used in the building, management, supervision, insurance, research and clerical costs, as well as other miscellaneous items.

As stated above, the Electricity Boards have some control over the quality of the meter, both when new and when it has been serviced. It is claimed that this factor has a very much greater effect upon the economics of metering than has hitherto been considered, and is, indeed, closely connected with the load/consumption characteristics.

While some meters may, at some stage of their life, tend to over-register, it is generally accepted, and the investigation proves, that the general tendency is to under-register with the passage of time. Incidentally, this is accentuated when a large percentage of the consumption is taken in the 0–10% sub-range. Although the increase of such under-registration will not be precisely linear with increase of time, it is not, certainly for periods up to 20 years, unreasonable to assume such linearity for credit-type meters.

If the period of time in service is T, the integrated net loss of revenue over any period of time is L, and the net loss after the first increment of time is l, and if it is assumed that this loss increases proportionally with T, then

$$L = lTdT$$

and integrating
$$L = \frac{l}{2}T^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If the cost of one complete maintenance operation is C the

* While testing meters *in situ* is feasible for large industrial installations, it has not been found possible to do this satisfactorily or economically for large numbers of domestic consumers' meters.

period T at which it is economic to service the meter is when $L = C$.

Hence, substituting C for L in eqn. (1), we have

$$C = \frac{l}{2}T^2$$

or

$$T = \sqrt{\frac{2C}{l}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

A reduction in the cost of maintenance has the effect of reducing the service period T, other factors remaining the same.

(3.4) Methods of Reducing Incremental Revenue Loss, l

The incremental revenue loss is dependent upon the annual consumption, W, the error of the meter, E_T, and the price per kilowatt-hour, p.

The Electricity Board can partly control E_T, and, as the present trend is for annual consumptions to increase, unless this increase is accompanied by a reduction in price per kilowatt-hour, it becomes ever more important to reduce E_T.

It is clear from Fig. 3 that the errors and the average under-registration are smaller for meters operating on higher loads. Consequently, if the percentage of the total energy registration in the lower sub-ranges of the meter can be reduced, l will be less. An increase in annual consumption would also probably lead to a larger percentage of the consumption being registered in the higher load sub-ranges, but only if the meter rating remained the same.

(3.5) Calculation of the Error of Total Energy Registration and Optimum Service Period

In order to assess the percentage error of total energy registration, reference should be made to Fig. 3.

For simplicity, if meters of the short- or long-range types only are considered, tests may be made at 5, 25 and 100% of rated current. The errors at these percentages of rated current are E_l, E_m and E_h, respectively. To obtain the error of total registration, E_l, E_m and E_h should be reduced by the percentage consumption at the percentage rated current indicated in Table 3. Obviously, close accuracy in weighting is not essential. The suggested weighting would be $E_l = 10\%$, $E_m = 60\%$ and $E_h = 30\%$. Average errors obtained after an average period of 10·9 years' service on 98 meters of one make were as follows: $E_l = -0{\cdot}5\%$, $E_m = 0{\cdot}0\%$ and $E_h = +0{\cdot}3\%$, giving a total energy registration error, E_T, of $+0{\cdot}04\%$.

An example of the calculation gives an idea of the values involved. The data are as follows:

Average annual consumption = 1 540 kWh.
Price per kWh = 1·25d.
Cost of a complete servicing operation = 25s.
Increase in error per annum = $-0{\cdot}05\%$, from which $l = 0{\cdot}96$d.

and

$$T = \sqrt{\frac{2 \times 300}{0{\cdot}96}} = 25 \text{ years}$$

If the loss rate were, from some cause, increased to 9·6d. the service period would be about eight years, but the annual cost would then have increased from 600/24d. to 600/8d., which approaches the annual charges in replacing the meter by a new one.

(3.6) Economic Factors Applied to Statutory Recertification Periods

If it is assumed that the statutory tolerances remain as at present prescribed, certain economic facts can be deduced.

When errors of a quantity of meters of a given make, type and period of manufacture are examined it is seen that the frequency of occurrence of 90% of the errors after service follows a Gaussian distribution reasonably closely. This leads to the unavoidable conclusion that a percentage of meters (perhaps very small) must be registering the total energy consumption outside the statutory tolerances.

The suggestion is made that the period of validity of certification be related to the percentage of meters registering outside the limits, on the basis that, if meters are within the limits, they are legally registering correctly and need not be withdrawn for recertification. With reference to those meters registering outside the limits, it is assumed for simplicity that the whole of the consumption has been measured incorrectly since the meter was installed, although it is realized that this may well not be the case. Since all consumers must bear the cost of obtaining and maintaining total energy registration of each meter within the statutory tolerances, it is considered reasonable to equate this cost to the total energy inaccurately registered, that is by those meters registering outside the statutory tolerances after a period of time.

The period can thus be reached when a certain percentage of meters are registering outside the statutory limits, and when their integrated energy registration will be such as to make it economic for all the consumers to have all meters recertified.

Although the calculation of this period might be based on a national average consumption of 1 540 kWh per annum, referred to in Table 1, it must be remembered that the larger number of domestic consumers have consumptions below the average, in which cases the monetary effect of lack of equity is less. The method of assessing a period on the above hypothesis is given in Appendix 9, together with numerical examples.

(3.7) Economic Factors Applied to Maintenance and Utilization

(3.7.1) Single-Phase Credit Meters.

In this Section meter economics are looked at from the point of view of the average error which directly affects the revenue of the supply undertaking. There are in the United Kingdom about 17 million meters of all types in use. The approximate total cost of maintaining a credit meter is 25s., half of which sum is expended upon the direct and overhead costs in the testing station. If the meters are to be serviced every 15 years the cost is £1 400 000 per annum. But if, as a result of reducing l, either by exchanging too large a meter for a smaller one at half the cost of a complete repair and overhaul, or by improving the quality of the meter such that the period T can be doubled, the cost is only about £700 000 per annum. It must be emphasized that utilization and maintenance are very closely allied, and the investigation shows that, by considering the effect of the load/consumption characteristics, economies can be achieved, although the present annual cost is not large in relation to the revenue. The current-carrying capacity of a meter has been erroneously understood as the rated current, whereas it may be several times that value in the case of a long-range meter and to a lesser extent of a m.c.r. meter.

Fig. 9 shows the effect on the total annual costs to the undertaking of installing one type of meter, X, where the total registration error after an average of 7 years is $-1{\cdot}4\%$ and the cost of maintenance is 25s. for varying servicing periods. The price per kilowatt-hour and the annual consumption are taken as 1·25d. and 1 540 kWh, respectively. On the same Figure the costs with another meter, Y, are shown, where the total registration error is $-0{\cdot}6\%$ after an average of 7 years. The minimum annual cost takes place at approximately 12 and 19 years, respectively,

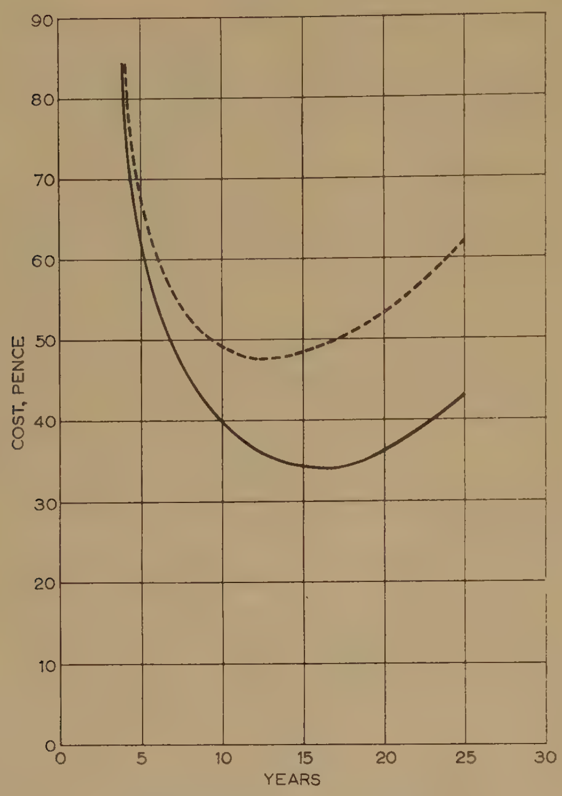


Fig. 9.—Annual cost curves for two makes of meter.
---- Type X. —— Type Y.

assuming that the rate of increase of error is constant. It should also be noted from Fig. 9 that a credit-type meter with about 60% smaller registration error results, in the example given, in a 50% reduction in annual cost. As the economic period increases, the rate of change of annual cost around the minimum becomes less. Therefore close accuracy in assessing the incremental loss l is not necessary where the period exceeds about 15 years.

(3.7.2) Pre-payment Meters, Flat-Rate Type.

The flat-rate type of pre-payment meter requires special consideration because the cost of maintenance is much greater than that of a single-phase credit meter and may be assessed at about 50s. per meter. There are some 3 000 000 of these meters in service in the United Kingdom, the average annual consumption being approximately 1 MWh per annum, which is considerably less than that of credit meters. The price per kilowatt-hour is, on the average, higher and will be assumed to be 3d., although it may be as high as 7d. in some cases. Load-analysing tests have not been made on pre-payment meters. However, assuming the same error weighting were employed as for credit meters, then, for one type of pre-payment meter which has a total registration error of $-0 \cdot 4\%$ after 15 years' service, the economic servicing period would be over 40 years. This is far in excess of the period that such meters normally remain in service.

(3.7.3) Polyphase Meters.

For the class of consumer supplied through polyphase meters, the annual consumptions are of a much higher order and the cost of maintenance and allowable tolerances are therefore relatively less than for single-phase meters. Load-analysing tests have not been made on industrial loads, but some indication of load factor is available from the use in many instances of maximum-demand indicators. Generally the load factors of such supplies are higher than those of domestic supplies, but, owing to the higher consumptions prevailing, the economic servicing periods will be considerably less than for single-phase meters, although the numbers of meters involved is also very much less than for the other classes. A method of dealing with the periodic servicing of one type of kWh meter with kVA maximum-demand indicator was developed which showed that it was reasonable to segregate such meters into groups of annual consumptions for the purpose of setting the time of a periodic test and replacement, if necessary. The result is given in Table 5.

Table 5

Annual rate of registration	Recommended maximum period between on-site tests
MWh	
100 to 500	3 years
500 to 2 000	2 years
2 000 to 10 000	1 year
over 10 000	6 months

(4) FUTURE RATINGS AND DESIGN OF METERS

Fig. 8 shows that the majority of domestic consumption is in the region up to 10 amp, and owing to diversity and national economic considerations this distribution seems unlikely to change appreciably for some time. Therefore a single-phase-meter specification which overlooks this aspect appears to need revision.

If it is generally agreed that ultimately a single-rating domestic house service meter is desirable, it would appear necessary in theory to provide for a torque at 50 amp (assuming a 240-volt single-phase supply) of about 40 g-cm to avoid excessive frictional errors occurring over a long period in service at load currents between 1 and 2 amp. This is based on the fact that long-range 5 amp meters with a torque of about 4 g-cm at full load have maintained their accuracy over long periods down to 20% load, and, in some cases, even less.

On the other hand, in view of the rather narrow range over which most meters measure the majority of the consumption, it is worth considering whether it would not be more economic to employ two current ratings, say, 20 and 60 amp m.c.r.

British Standard ratings are 10, 40 and 80 amp m.c.r., but it is suggested that a rating of 80 amp for domestic supplies is not required, although, in special cases, such as commercial premises, they are necessary. The tests in sample D clearly showed that there was little benefit in introducing an intermediate maximum continuous rating of 20 amp between 10 and 40 amp.

Turning now to the range of the meter over which it should measure accurately. Maximum accuracy is required at between 1 and 20 amp. If two ratings of meter are employed, none of which would have an overload accuracy, there would then appear to be no point in the low-load accuracy being considered below one-tenth of the maximum continuous rating. This would presumably result in reducing costs of manufacture and maintenance and the resulting annual charges. At present, for a new meter these annual charges, on a 15-year depreciation period and long-term investment rate of $5\frac{1}{2}\%$, are 7s. 6d. per annum. However, the replacement of meters is also controlled by the availability of capital.

(5) UTILIZATION OF EXISTING METERS

Since the actual choice of meter rating is often in the hands of local staff based on a branch or district office, it is necessary to provide some easy formula to enable them to select

a reasonable rating of meter for installation. It will be seen from Table 3 that no improvement was obtained in sample D by installing meters on the basis proposed in Table 2. This is due to the great range of diversity of use of the apparatus installed. It was thought that there might be better correlation between annual consumptions and maximum demands, and these were plotted as a scatter diagram in Fig. 6. For annual consumptions of up to about 700 kWh per annum, the maximum demand does not exceed about 12 amp, after which there is a sudden increase in possible maximum demand to about 30 amp for annual consumptions of 3 MWh, followed by a more gradual rise of maximum demand to 50 amp for high annual consumptions. In Fig. 10 these limits of annual consumption have been indicated, and horizontal and vertical lines have been shown at the practical upper measuring limits of long-range meters of 5,

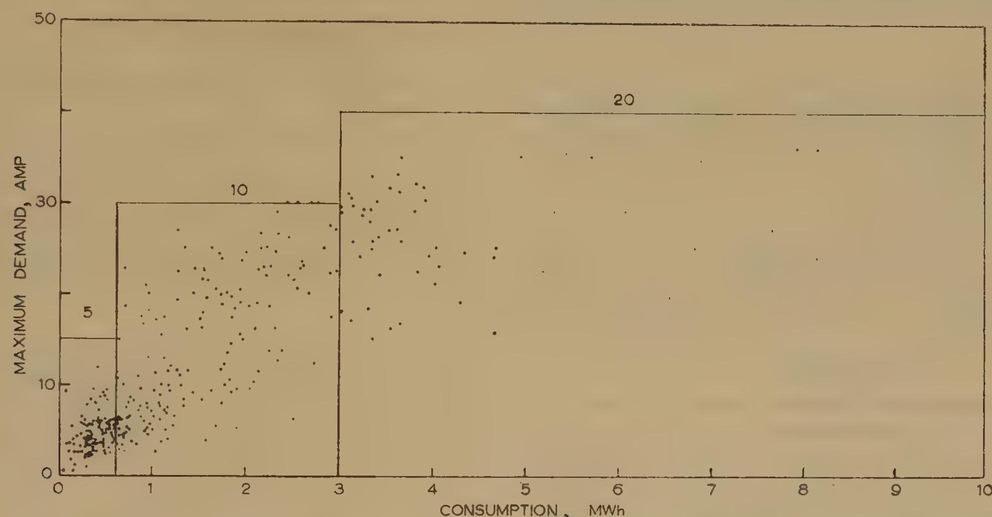


Fig. 10.—Fig. 6 showing suggested relation between annual consumptions and long-range meter ratings.

10 and 20 amp and annual consumptions of 700 and 3 000 kWh, respectively. In order to ascertain the effect of installing meters on this basis, those records of analysing meters which conform to this suggestion were extracted from the tests. The proportion of meters with percentage consumption in the 0–10% sub-range is indicated in Table 6. Furthermore, the percentage consumption in that sub-range of all the meters so installed is reduced to 8%, which is a significant improvement over the figures of 16% obtained in the investigation. The suggested basis for installed meters on existing consumers' premises is to apply Table 7 after reference to meter-reading folios.

Table 6

SELECTED CONSUMERS' CONSUMPTIONS BELOW 10% OF MARKED CURRENT

Percentage of consumption registered below 10% marked current s.r. or l.r.	Consumers		
	Number	Percentage	Cumulative
0 to 5	27	22	22
5·1 to 10	32	26	48
10·1 to 15	8	6	54
15·1 to 20	18	15	69
20·1 to 25	13	10	79
25·1 to 50	19	15	94
50·1 to 100	7	6	100

Table 7

Annual consumption	Maximum continuous rating
kWh	amp
Up to 600	10–15
600 to 3 000	20–30
over 3 000	40–50

For new consumers the suggestion is made that either a 10 amp long-range meter, when such an instrument is in stock, should be fitted, or a 40 amp m.c.r. meter when a new one has to be purchased. These meters could be changed after the first year of service where it was shown to be necessary, unless there was good reason to think that the consumption would materially increase. These suggestions are made to cover the normal cases, but there would, of course, be other instances where local conditions would have to be considered. If the suggestion for the more efficient use of meters were adopted it would appear logical to raise the lowest test limit for certification from 5 to 10% of rated current on long-range meters, and it is apparent that testing station costs and the economic period of re-test would be thereby reduced.

(6) CONCLUSIONS

Throughout the paper the errors of the meters have been measured with current as the sole variable, and account has not, in general, been taken of the initial calibration errors of the meters at the time of installation. Their average is, however, usually small in relation to the average of the errors of the meters after service. The standard deviation of the errors is, of course, controlled indirectly by the operation of the certification procedure.

The whole investigation shows that the consumers' load/consumption characteristics have a considerable influence upon metering practice, and a knowledge of the facts about such characteristics enables a realistic attitude to be adopted resulting in substantial savings in overall metering costs.

The facts regarding the findings in the investigations have been set down in the paper, but, owing to the complexity of the problem and the interdependence of factors, no specific recommendations have been made.

It is hoped that some of the suggestions put forward as a result of the investigations will be of service to meter manufacturers and the electricity supply industry in providing an efficient metering service to the consumer.

(7) ACKNOWLEDGMENTS

The author wishes to place on record his sincere thanks to his many friends in the industry who have given their constructive criticisms, help and encouragement during the period of this investigation. He wishes particularly to thank his colleagues Mr. S. A. Daines for helpful suggestions, Mr. R. J. Luck for assistance in preparing Figures and Tables, and also Mr. P. Schiller and his staff for the collation and analysis of the figures derived from the investigation. Finally he wishes to express his gratitude to the Chairman and Chief Engineer, respectively, of the Eastern Electricity Board for permission to prepare and publish the paper.

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(9) APPENDIX

(9.1) Assessment of a Statutory Period of Meter Recertification

If the average value and the standard deviation of the errors of total meter registration of meters with similar characteristics and period of service are known, and shown to be normally distributed, the approximate percentage of meters which might be expected to have registration errors exceeding certain given limits can be obtained by reference to Table 22 of B.S. 600: 1935, but taking into account the displacement of the curve with respect to zero average error. The average error of the meters exceeding the statutory limits x, where $x_1 = +2\cdot5\%$ and $x_2 = -3\cdot5\%$ may be assessed for the meters, and by adopting expression (2) in Section 3.3, a period T may be obtained.

Two examples are given using figures of errors obtained on meter A. Example 1 uses the weighted figure for the average and standard deviation, while example 2 estimates the recertification period assuming the extreme case that all the consumption was taken below 10% of the rated load current.

TYPE A METER

	Actual %	Weighted %	Standard deviation %
Average error at 100% rated current	−0·7	−0·21	0·21
Average error at 25% rated current	−1·1	−0·66	0·538
Average error at 5% rated current	−3·3	−0·33	0·265
Average error of total meter registration	—	−1·2	—
Standard deviation of total meter registration	—	—	1·013
Number of meters in sample ..	29		
Average number of years in service	7		

	Example 1	Example 2
Number of meters	29	29
Period of service, years	7	7
Average errors of total meter registration	−1·2%	—
Average error below 10% load ..	—	−3·3%
Standard deviation	1·0%	2·65%

Example 1.

$+2\frac{1}{2}\%$ *limit*

$$t_1 = \frac{x_1 - \bar{x}}{s}$$

$$= \frac{2\cdot5 - (-1\cdot2)}{1\cdot0} = 3\cdot7$$

$-3\frac{1}{2}\%$ *limit*

$$t_2 = \frac{x_2 - \bar{x}}{s}$$

$$= \frac{-3\cdot5 - (-1\cdot2)}{1\cdot0} = -2\cdot3$$

From Table 22 of B.S. 600:

Chance of meters having errors greater than +2·5%	Negligible
Chance of meters having errors less than −3·5%	0·0107
Sum of chances of meters having errors outside statutory limits	0·0107

The average error of these meters outside limits is obtained by reference to Table 22 of B.S. 600: 1955 by interpolation of a t_3 value,

$$\text{where } \frac{0\cdot0107}{2} = 0\cdot0054, \text{ or } t_3 = 2\cdot6$$

Average error of the meters outside the limits is

$$t_3 s \pm \bar{x}$$
$$= 2\cdot6 \times 1\cdot0 - (-1\cdot2)$$
$$= -3\cdot8\%$$

Applying the formula

$$T = \sqrt{\frac{2 \times 100C}{\frac{y}{T_1 100} \times a \times W \times \frac{P}{12}}}$$

Where $100C$ = Cost of testing 100% meters at C shillings each.
y = Average error of meters outside limits.
T_1 = Number of years the meters have been in service.
a = Chance of errors outside the statutory limits, %.
W = Annual consumption, kWh per meter.
p = Price per kWh, pence.

$$T = \sqrt{\frac{2 \times 100 \times 25}{\frac{3\cdot8}{7 \times 100} \times 1\cdot07 \times 1540 \times \frac{1\cdot25}{12}}}$$
$$= 73 \text{ years}$$

Example 2.

$+2\frac{1}{2}\%$ *limit*

$$t_1 = \frac{x_1 - \bar{x}}{s}$$

$$= \frac{2\cdot5 - (-3\cdot3)}{2\cdot65} = 2\cdot2$$

$-3\frac{1}{2}$% limit

$$t_2 = \frac{x_2 - \bar{x}}{s}$$

$$= \frac{-3\cdot5 - (-3\cdot3)}{2\cdot65} = -0\cdot075$$

From Table 22 of B.S. 600:

Chance of meters having errors greater than +2·5% ..	Negligible
Chance of meters having errors less than −3·5% ..	0·4602
Sum of chances of meters having errors outside statutory limits ..	0·4602

The 't_3' value for the average error of meters outside the limits is

where $\frac{0\cdot4602}{2} = 0\cdot2301$ to $t_3 = 0\cdot75$

The average error of the meters outside limits is

$$ts \pm \bar{x}$$
$$= (0\cdot75 \times 2\cdot65) - (-3\cdot3)$$
$$= -5\cdot3\%$$

$$T = \sqrt{\frac{2 \times 100 \times 25}{\frac{5\cdot3}{7 \times 100} \times 46 \times 1540 \times \frac{1\cdot25}{12}}}$$

$$= 9\cdot5 \text{ years}$$

The two results demonstrate the necessity for reducing the consumption at low loads by installing appropriately rated meters and applying a realistic weighting to meter errors.

For the sake of comparison the results of tests on a sample of meter B reveal the following statistics:

Type B Meter

	Actual %	Weighted %	Standard deviation %
Average error at 100% rated current	+0·09	+0·027	0·127
Average error at 20% rated current	+0·14	+0·084	0·44
Average error at 5% rated current	+0·04	+0·004	0·10
Average error of total meter registration	—	+0·115	—
Standard deviation of total meter registration	—	—	0·667
Number of meters in sample ..	30		
Years in service Average	13		

It is evident that meter B will merit a certification period much in excess of meter A.

If sampling tests on meters with similar technical characteristics are made periodically, then, by observing the standard deviation and the average error, the rate of deterioration can be assessed, and a period deduced by which all the meters of that type must be recertified.

Owing to the presence of the square-root sign, high accuracy of assessment of errors is not vital, and the annual cost of certification for long periods of service is small. It also becomes clear that, in general, the meters will probably be withdrawn from service by the supply undertaking owing to net under-registration before a recertification period calculated on the above basis becomes operative.

Finally, a single statutory recertification period for all meters is likely to add to the costs and result in the quality of meters being worsened.

It is the purpose of the meter sampling tests, which were proposed by a Panel of the Ministry of Power Measurements Technical Advisory Committee, to obtain factual information on the rate of deterioration, standard deviation and average error of meters in service.

DISCUSSION BEFORE THE MEASUREMENT AND CONTROL SECTION, 3RD MARCH, 1959

Mr. H. S. Petch: The paper is timely, and comes at a turning point in metering history when the long sleep of eternal certification has given way to short 15-year naps. The author rightly draws attention to the economic significance of this step, and it is interesting to compare the trends in meter legislation in the United States and this country. In the former, a liberalizing policy is discernible, having an economic basis. In this country we are tightening up, primarily in the interests of equity. The supply industry is supposed to adjust its tariffs to divide its costs equitably. But attempted perfection in such egalitarianism is liable to push those costs to the point where nobody can afford the supply. A qualified person should make a study of the economics of equity.

The Introduction shows that meter maintenance is now costing about 1% of the revenue collected. Even with this standard of maintenance the quoted figures of average registration losses from slow meters indicate how very serious this revenue loss would become if the responsible meter departments did not earn the 1% which they cost.

The last two sentences of Section 2.7 and the closing words of Section 2.9 should be particularly emphasized, because they are so often overlooked by those who install meters.

In Section 3.2 the author mentions the consumer's right to an official test at any time. Electricity Boards also have this right, and, in this general connection, there appears to be a growing concern with the rights of consumers and duties of Electricity Boards to the neglect of the equally valid converse.

The notions which the author advances in Section 3.6 provide a rational basis for a legal recertification period. The development of these notions in the Appendix leads to some startling conclusions, but this does not invalidate the notions.

In the second worked example in the Appendix, the author uses the national average consumption of 1540kWh. As this example deals with the case of all consumption taken at low load, it might be better to use a lower annual consumption. If this is done and 750kWh per annum is taken, the service period becomes 15 years, which is perhaps more realistic.

In Section 3.7.1 the author draws attention to misapprehensions concerning the current-carrying capacity of meters. In our own Board we have tried to deal with this problem by assigning a kilowatt rating to all meters, and giving some guidance on appropriate ratings.

With reference to Section 3.7.2, I suspect that the tariffs enjoyed by prepayment consumers do not wholly reflect the real costs. If they did, and the tariffs were appreciably higher, it might then be appropriate to apply the same reasoning to credit and pre-payment meters, and the calculated service periods would more nearly approach practically determined values.

I agree with the author that a revision of B.S. 37 Part 2 is now due. There is a case for only one size of domestic meter because of the heavy costs of changing meters. Such a single meter size could emerge if 50amp were accepted as the present ceiling for domestic currents, if it were accepted that currents exceeding 30amp need not be registered with extreme accuracy, and that sustained accuracy is vital over the range 1·5–6amp. It might be called a 15/30amp meter, following I.E.C. practice.

The author suggests that testing only down to one-tenth load might reduce manufacturing and maintenance costs. I question

this, because I feel that one-twentieth load tests, even if only applied on a sampling basis, are really necessary quality checks. If we arrived at a single meter size as discussed above, official tests on every meter at such very low loads would seem unnecessary.

Finally, I should like to know whether the author can give some idea of the cost of the four sample tests.

Mr. M. Whitehead: The author's persistence in obtaining this important information is much appreciated and, in particular, the increase in sample size to about one in 40 000 from one in 150 000. However, it is unfortunate that the presentation of meter errors after each year's service has not been continued as it would have obviated the serious assumptions that the average of the initial errors was small (Section 6) and that errors increase linearly with time (Section 3.3).

From the supply undertaking's viewpoint, the primary function of meters in a large group of small consumers is to prevent waste and the possible engineering breakdown of the system. The consumer interest is that the individual meter should not have a positive error exceeding a reasonable amount and that the total bill for energy and metering should be a minimum. Considering consumers in the mass and concentrating on average consumption and mean error, $\bar{x}$, which is said to become increasingly negative, long theoretical certification periods are attained.

However, consumers are individuals, and must be considered as such. If this point of view is accepted, attention must be turned from average consumption and $\bar{x}$ to individual consumption and the tails of the distribution curve where the errors are large. There are dangers in reaching conclusions from the tails of the curves and it may require much more careful sampling. It would be of considerable interest if the exercise could be repeated considering only the consumer interest, when it is likely that the theoretical certification periods would be very much shorter than those quoted in the paper.

Two individual points on which the author may care to comment are, first, the large differences between errors obtained 'on site' and in the test room (Table 4), and secondly, although 'max' meters have been in use for seven years there are apparently none in the samples.

Mr. S. Howarth: The author has rightly stressed the economic factors, and we are not unmindful of such considerations. The problems of obtaining factual information and assessing the results of sampling millions of meters of various sizes, types and categories can only be dealt with satisfactorily by statistical application, and it is significant that other countries are now adopting such methods.

The load investigations comprise 400 samples out of a total of 15 million meters, and I should have thought that a larger cross-section was necessary to obtain a true picture. I would like to have seen this particular research coupled with the Electricity Council's utilization sample survey. By doing this, a great deal of useful information would have been obtained from 12 000 consumers on the size of meters in relation to annual consumption and installed loads. From the point of view of establishing consumers' consumption characteristics, I would have preferred the ranges of the analysing meters to be finer and more numerous.

Since the war there has been a trend to fit large meters initially in anticipation of load growth, thereby saving replacement costs. The evidence of the Electricity Council's utilization research revealed a large block of small consumers, and undoubtedly where an anticipated load increase has not materialized, over-metering exists. Whilst the question of costs cannot be ignored, the law requires consumption, whether large or small, to be measured within legal limits, and this should not be overlooked in deciding the policies with regard to meter size.

The question has been raised about the difference between prepayment and credit-type meters. A different set of circumstances exists, and a single formula for the estimation of the average error would be unlikely.

With regard to the suggestion of raising the lower testing limit, whilst over-metering continues to be practised it is doubtful whether a change from 5 to 10% is justifiable.

As to the method of assessment of the statutory period of certification, I find it difficult to accept that the average error obtained from a single set of test figures is linear throughout the service life of the meter, or that the chance of meters with errors outside the limits remains unaltered. Furthermore, the suggested method offers no incentive to reduce maintenance costs, and it seems anomalous that a reduction in these costs has the effect of reducing the service period of the meter.

Mr. Petch mentions the American relaxations. These amount to extending the service period from about 7 years, thus bringing it more into line with our requirements.

Mr. A. Felton: In Section 3.3 the author develops a formula for the service period of a meter, and makes considerable use of it in succeeding Sections and in the Appendix. The formula is based on the assumption that under-registration will increase linearly with time, but the only justification for this is that it is not unreasonable. Surely this is a very flimsy foundation on which to base our calculations of economic service life. It would, in many ways, be more reasonable to assume an increase proportional to the square, or other power, of time. This would give very different results. Thus, although the service period appears to have been calculated, it is, in fact, no more than a guess.

Mr. O. Howarth: Are the sampling areas limited to a particular part of the country, or has the author been able to obtain an average sample of the country as a whole? It has been stated that meter errors do not matter, because, if the meters are too slow, the Boards will increase their prices and if they are too fast they will lower them. When I buy a pound of butter it is no consolation to me to be told that, if I only get 15 ounces, it is equitable because all the other purchasers get the same and the price has been adjusted accordingly. Similarly, when I buy a kilowatt-hour of energy, I want a kilowatt-hour and no less, and the argument that meter errors do not matter because the price is adjusted is wrong.

Mr. M. J. Mehler: The histograms in the paper appear to show that nearly all meters tend to become slow after a number of years. Tests carried out a few years ago by the Midlands Electricity Board on 12 different makes of meter, after 15 years on circuit, found errors of up to 8%, both fast and slow. The average error was almost zero.

It would therefore appear that the only reason for changing meters is to be fair to the consumer. There is no financial advantage to the Boards in changing them.

Mr. A. M. Strickland: Some time ago a French undertaking carried out work similar to that described by the author, and the results were published about 1930. They arrived at the same kind of conclusion, and I believe that the curves showed ultimately that it did not matter at what point meter changing was done in the period of 7–12 years.

The characteristic of some meters going faster at low loads, and then only until final slowing occurred, was also shown on the curves.

Mr. A. J. Baggott (*communicated*): It is undoubtedly in the interests of the Board and the consumers to replace inaccurate meters from time to time, and this need can be based almost exclusively on the desirability of maintaining equity between

consumers. The opening statement in Section 3.3 is largely academic and is a means of justifying a large expenditure by applying too narrow an economic theorem. Perhaps one should consider an extreme case in which all meters were outside the statutory limit in one direction, having errors close to each other. Equity would be maintained to within a close limit. Under these circumstances, according to Section 3.3, a case would be made out for a costly overhaul maintenance programme, whereas all that would be needed would be a tariff revision. A case cannot be made out for maintenance on these grounds, nor is it realistic to place a definite limit on the validity of certification of all meters, irrespective of their type or age.

Everyone's interests would be served, at minimum cost, by replacing meters only in proportion to the errors which exist. The average errors could be determined from the results of, say, 1% per annum samples selected statistically, and the number taken off circuit for overhaul would be determined by, and selected in, the light of the results. In assessing the number to be changed, it is suggested that two factors be considered:

(*a*) The number outside the accuracy band of, say, 98–102%.
(*b*) The number of meters giving figures greater than 102%.

A simple formula, weighted in favour of the first factor, could then be applied. It is suggested that the samples be chosen from those meters having longest service without overhaul, and that the on-site tests be reduced to two loads, namely 100 and 10%. Weighting of the top load errors would be advisable, and the average error could be, say, $\frac{1}{4}$ (3 × 100% load error + 10% load error).

Such a programme would permit the gradual improvement of the accuracy of the meters on circuit at appreciably less cost than the present statutory rate of change, and maintain the desirable equity between consumers.

Monsieur S. Rambaut (*Belgium: communicated*): The author questions whether knowledge of the load/consumption curve on the one hand, and knowledge of the curve of the frequency distribution of the meter errors on the other, are of such a nature as to enable the period of reservicing of meters to be determined.

The principal criterion considered in the paper is the calculation of the loss of consumption resulting from under-registration. When this loss integrated with time equals the cost of servicing, retesting is justified, and, at the same time, the number of years between two retesting periods is obtained.

The calculation of the loss registered by the meter is based on different hypotheses. One (Section 3.5) is that the resulting total error in kilowatt-hours varies by $-0\cdot05\%$ per annum; the other (Section 9.1, example 1) assumes that the loss arises only from meters which are found to be outside the limits of $+2\cdot5\%$ and $-3\cdot5\%$. A third hypothesis (Section 9.1, example 2) assumes that all the consumption is taken at a load which is below 10% of the nominal current rating of the meter. The results thus obtained vary considerably. Periods of servicing of 24, 73 and 9·5 years, respectively, are obtained.

In the first hypothesis, the author presupposes a linear variation of the mean weighted meter error, which is not necessarily the case; the fact is that it is particularly at the low loads where the errors change the most.

In the other two hypotheses, the author assumes that the annual loss is a constant function of the probability that the errors exceed $+2\cdot5\%$ or $-3\cdot5\%$.

In order to determine the period of retest of a given type of meter, it is necessary to know in advance the variation of the errors as a function of time, which is unfortunately not known. Furthermore, these considerations apply only if the tariff is the same for all the kilowatt-hours consumed.

Thus, whatever methods are used to determine the period of retest of the meters, they can only give relative and not absolute values, i.e. the periods of overhaul must be calculated for different types of meter by the *same method*. Thus one would obtain comparable figures between the two, namely relative to each other.

However, re-servicing the meters cannot be based solely on the economic criterion, but it must also depend on the statutory and legal criteria which give the guarantee to the two parties concerned (the consumer and the supplier) that a sufficient percentage of meters have errors within the legal limits.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. L. B. S. Golds (*in reply*): Several speakers criticize the assumption that meters increasingly under-register year by year at a linear rate. If the average errors of the histograms given in Figs. 1(*a*) and (*b*) of Reference 1 are calculated it will be found that the increase in minus error is, for practical purposes, linear up to 15 years. There will, of course, be certain types of meter where this is not true, and furthermore it is not yet known after what period the rate of increase in error departs from linear. I suggest that tests be undertaken periodically on meters which have been in service for periods in excess of 15 years, for which purpose the order specifying the period of validity of certification might be modified to enable this factual information to be obtained. Although the formula for the economic maintenance period is based on the assumption of linearity, I pointed out in Section 3.7.1 that, for long service periods, great accuracy in ascertaining the total net loss of revenue is not necessary in order to arrive at an approximation of the service period.

In reply to Mr. Petch I feel that the approach to the study of the 'economics of equity' might be along the lines indicated in Section 3.6 and the Appendix. Owing to limitations of space and scope of the paper I could not follow up this line of thought to the point where the economics of the legal tolerances for various classes of consumers could be discussed. In the second example in the Appendix the same average consumption was used to reduce the number of variable factors, but Mr. Petch's point is a valid one and 750kWh would be more realistic. The economics of adopting one long-range meter rating instead of two or more short-range meters require examination.

The costs of the 200 load-analysing meters were approximately £30 each, while I would estimate the labour and clerical costs of the four investigations to total about £5000. This is a small price in relation to an annual saving of £500000 resulting from an extension of the recertification period from 15 to 20 years. In addition, information is obtained which may result in economies in meter design requirements and utilization.

Mr. Whitehead refers to the initial errors of meters when first commissioned. This may have been valid where the period of service commenced before the operation of the Meters Act. National tests comprising a survey of meters after service will, it is hoped, provide data on the change of meter error with time. For the reasons given in the earlier paper it was necessary to obtain the data revealed in this paper before such a survey could be undertaken. He suggests that consideration be given to 'the tails of the distribution curve', but care must be taken that they 'do not wag the dog'. The large variations, owing to physical movement of the meter, of errors on low loads in individual cases appear to be due to disturbance of grease, and it has been found that all types of meter do not vary in the

same manner. In view of the relatively small average proportion of the consumption at such loads, as revealed by the load-analysing meters, these variations have not yet been further investigated.

It is unfortunate that collaboration with the utilization research survey, as suggested by Mr. S. Howarth, did not take place. There is no reason, other than capital cost and bulk, for the number of load-analysing meter sub-ranges not being 'finer and more numerous'. The use of the meter saves much laborious analysis of charts and gives a much longer effective measuring range than graphic recording instruments. The addition of a maximum-demand indicator would, however, also be desirable.

In view of the acknowledged trend of meters to under-register generally with time, obviously the minimum annual cost occurs when the integrated loss over the service period is equal to one maintenance operation. There is therefore a strong incentive to reduce maintenance costs.

For the reasons already stated, I do not accept Mr. Felton's stricture, and he gives no specific reason for saying that my assumption of linear increase in error is unreasonable.

It seems desirable to let the areas sampled remain anonymous, but I can assure Mr. O. Howarth that they cover areas broadly representative of the country. The kilowatt-hour is the unit upon which energy is sold and upon which supply statistics are based, and therefore that unit must, if for no other reason, be measured within reasonable tolerances and with a small average error.

I am not clear what Mr. Mehler infers by the average error on meters after 15 years' service being almost zero. If he means an error of $1 \cdot 0\%$ slow, this represents a large sum of money when related to the Midlands Electricity Board's revenue derived from domestic meters.

The earlier investigation in France referred to by Mr. Strickland is interesting, and, of course, relates to 'short-range' meters. These present investigations, however, refer to long-range meters.

Mr. Baggott appears to have followed my line of approach suggested by the worked examples in the Appendix. I agree that the period of validity of meter certification could be related to tests on sample meters in service. I understand that certain States in the United States adopt this form of procedure. The main purpose of the investigation was to obtain 'weighting' factors. That tariff revisions could take into account slow meters, as suggested by Mr. Baggott, is not realistic and would probably not be acceptable to a Committee on Weights and Measures such as that which reported in 1951.

Monsieur Rambaut draws attention to the various periods for retesting which are obtained. It is true that all the variables need to be carefully studied so that metering may be efficient and equitable to all parties, and that, if possible, the right method as well as the same method should be employed for the calculations.

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TURBO-GENERATOR PERFORMANCE UNDER EXCEPTIONAL OPERATING CONDITIONS

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(*The paper was first received* 15*th October, and in revised form* 8*th December*, 1958. *It was published in January*, 1959, *and was read before the* NORTH-EASTERN CENTRE 26*th January, and* THE INSTITUTION 5*th February*, 1959.)

SUMMARY

A series of tests was made to determine the performances of a normally inactive and a continuously acting turbo-generator automatic regulator, and the opportunity was also taken to check some operating conditions which do not often arise in normal service. The paper gives typical details of tests on a generator operating at considerable leading power factors with different excitation-control systems. Instances of instability and out-of-step running occurred and were recorded, as also were tests on the machine as an asynchronous generator at various slip frequencies. A method of synchronizing, previously discussed but not tested and recorded in this country, was used in which the running generator was connected to the busbars and the excitation applied after a time interval. Conclusions arising from the investigations are given.

(1) INTRODUCTION

In addition to the improved performance of the recently developed, continuously acting automatic regulators in the normal lagging-power-factor operating region, it has been claimed[1] that these regulators will permit safe operation at power factors appreciably more leading than was possible with earlier normally inactive regulators. Such a performance could enable the generator short-circuit ratio to be reduced, resulting in savings in the weight per megawatt of generator output. Economies can be effected by increasing the size and output of turbo-generators, but transport-weight limitations tend to restrict the building and testing, in the makers' works, of very large generators. A weight saving, if only of the order of 10%, by reduction of the short-circuit ratio is therefore of considerable importance.

With the advent of 275 kV transmission, and even higher voltages in some countries, a leading power factor will be required at exporting stations under certain conditions of system load. The testing of both a continuously acting and a normally inactive regulator, particularly under leading-power-factor operating conditions, was therefore a matter of prime importance. Stability of excitation is not, however, the only factor to be considered when operating large highly rated generators at leading power factors, since additional heating at the ends of the stator core can cause output limitations. Until machines with very high stator-ampere-conductor loadings have been commissioned, the end-heating effects can best be estimated from extrapolation of tests on existing generators.

Until comparatively recently, little has been published regarding the possibility of continuing to run a turbo-generator on load in the event of loss of excitation or of resynchronizing should pole slipping occur. Some operators understand that, if inadvertent tripping of the field breaker occurs, they should reduce load to about half the rated output and reclose the field breaker as quickly as possible. However, the practical limitations of asynchronous running are by no means completely realized, and a study of the problem was undertaken.

A procedure, which has not so far been considered necessary in this country, although it has been used to some extent in Eastern Europe, is synchronizing a running generator by first switching it on to the busbars and then applying excitation. In the event of loss of synchronizing equipment, such a technique has been considered as a temporary measure, but, prior to the tests described, it had not been put into practice.

(2) TEST PROGRAMME

The tests reported in the paper were made on one of four standard 60 MW hydrogen-cooled turbo-generators at Stella North power station near Newcastle upon Tyne. A few results of some similar tests made on machines at other stations are given for comparison.

(2.1) Details of System and Machines

All the Stella North generators were connected through step-up transformers to a 132 kV system which was connected, either directly or indirectly, to a 132 kV system based on Stella South power station, where five 60 MW machines and step-up transformers were installed. Both 132 kV systems were connected to the 275 kV system through up to four 120 MVA auto-transformers at Stella West substation. A 100-mile 275 kV double-circuit line connected Stella West to Monk Fryston substation in Yorkshire, which was in turn connected to the 275 kV system further south. The fault level at the 132 kV busbars at Stella North (excluding infeed from the test machine) varied over the period of the tests between 2 500 and 3 000 MVA.

All nine sets at the two Stella stations have main and pilot exciters driven by the main shaft through reduction gearing. One of the generators at Stella North was chosen for the tests because additional thermocouples had previously been fitted to the stator to facilitate measurement of end heating when operating at leading power factors. Particulars of this machine and its step-up transformer are given in Table 1.

(2.2) Tests

Over 130 tests were made in July and October, 1957, and March, 1958. These included: operation of the generator under hand-control of excitation, and with two different types of automatic regulator; stability-limit tests; suddenly changing the voltage applied to the regulator; and suddenly altering the impedance between the step-up transformer and the 132 kV busbars. Stator end heating was measured under different conditions, and out-of-step operation, asynchronous running and self-synchronizing tests were recorded.

(2.3) Measuring Equipment

Measurements were made by oscillographic and pen-on-paper recorders and sub-standard bench instruments. The rotor angle

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Table 1

PLANT DATA AND SYMBOLS

Generator, rated at 60 MW at 0·8 p.f. lagging, 11·8 kV, 3 670 amp and 3 000 r.p.m.

Short-circuit ratios	
With non-magnetic end-rings	0·59
With magnetic end-rings	0·62
Synchronous reactance, X_d, %	200 on 75 MVA
Transient reactance, X'_d, %	20
Sub-transient reactance, X''_d, %	13
Negative-phase-sequence reactance, X_2, %	16
Direct-axis time-constants, sec	
Transient open-circuit, τ'_{d0}	11
Transient short-circuit, τ'_d	0·8
Sub-transient short-circuit, τ''_d	0·035
Inertia constant, H, kW-sec/KVA	4·64
Field current at no-load rated voltage (non-magnetic end-rings), amp	300
Rotor angle with respect to infinite busbar	θ

Generator Step-Up Transformer

Rated output, MVA	72
Ratio (no load) 11·8 kV delta/141·6 kV ± 10% star in ± 7 steps	
Tap 5	11·8/147·7 kV
Tap 15	11·8/127·4 kV
Reactance, based on 72 MVA and 11·8 kV between l.v. terminals, %.	
Tap 1	12·85
Tap 8	12·37
Tap 15	11·8

was indicated in the control room by means of a magslip, which compared the phase of the stator voltage of the main machine with that of a tacho-generator coupled to the main shaft. This angle was also measured during the second series of tests by apparatus giving visual indication and by a photographic record at the generator by stroboscopic means.[2]

(3) GENERATOR OPERATION IN THE UNDER-EXCITED REGION

(3.1) Steady-State Stability

If, for any particular load condition, the excitation of a synchronous generator is reduced below a certain critical value, the rotor field strength is not sufficient to hold the rotor in synchronism with the rotating stator magnetomotive force, and the rotor will increase in speed resulting in pole slipping and instability. The major factors which determine the critical minimum excitation are the method of excitation control, i.e. hand or automatic regulator, and the type of regulator used. In order to avoid operating too near the region of instability, Central Electricity Generating Board power-station control-room operators are now provided with charts which indicate the minimum excitation for any load, the values also being related to machine voltage. Thus, in operating machines at unity, or slightly leading, power factors, as can occur when supplying an extensive cable system or long transmission line, the operator should not reduce the excitation below the safe values.

In determining these safe values, a stability margin, expressed as a percentage of rated load, is allowed. For hand control, a margin of 20% is invariably used under full-load operating conditions, and, owing to the possibility of the turbine picking up relatively greater load increments when operating at fractional loads, a margin of 35% is allowed at no-load. Under the control of a normally inactive automatic regulator the corresponding margins are 10% and 30%. Prior to the recent tests, the safe limit of power-factor operation with high-response continuously-acting regulators had not been established.

In order to prevent automatic regulators reducing the excitation below safe values, in the event of a sudden rise in system voltage, minimum excitation, or leading-reactive-power limiters, have been developed over the last few years as part of the regulator equipment. By comparing the leading reactive power, load and voltage, or by other methods such as measurement of rotor angle, the limiter can be set to come into operation at the prescribed stability margins and so prevent a serious reduction, or, if desired, give a slight increase, of excitation.

The Stella tests, in comparing the performance of a turbo-generator near the stability limit under hand- and automatic-regulator control, also indicate the effectiveness of reactive-power limiters. It is largely because of the safeguards provided by such limiters, and the provision in control rooms of power charts or minimum-excitation curves, and, in some cases, vectormeters, that special forms of stable-operation supervision such as rotor-angle indication have not, in general, been provided for control operators.

(3.2) Stability-Limit Tests

The maximum leading-reactive-power operating conditions, as determined from the tests on hand, normally inactive regulator and high-response continuously-acting regulator control of excitation, are given in Table 2. The reactive-power limiters were not in circuit during these tests. When obtaining such limits for any one load condition, in particular for the continuously acting regulator, it was interesting to note the reduction of excitation to a minimum value at the point of theoretical instability (rotor angle, $\theta = 90°$), followed by an increase of excitation as the leading reactive power was increased still further. The approach to the limit of stability was indicated by a slight oscillation of excitation and generator output. A very small increase in reactive loading rapidly increased the magnitude of the oscillation, and very careful control of the regulator rheostat was then necessary to avoid pole slipping.

While it is not envisaged that such advanced leading-power-factor operation of generators will be required, it is necessary to know the limits under any particular system of control. An operating power chart for the Stella machine, at rated voltage based on calculations using the short-circuit ratio, is shown in Fig. 1. The test steady-state stability limits, adjusted for a constant machine-terminal voltage of 11·8 kV, and the normally-inactive-regulator stability-limit line, with margins of 10% and 30% of rated load at full load and no load respectively, are shown. In practice, the transformer voltage-drop under leading power-factor conditions has the effect of lowering the machine terminal voltage and the power and reactive outputs.

Tests have also been taken on other generators near the limit of stability with alternative designs of continuously acting regulators, and some typical readings are included in Table 2.

An explanation of the factors determining the steady-state stability limit is assisted by reference to Fig. 2. At rotor angles less than 90° the rotor-angle/output-torque curves have a positive slope, and with constant steam input the machine is in stable equilibrium at any fixed excitation above a prescribed value. This is because any excess driving torque increases the rotor angle and hence the output torque, and vice versa.

At rotor angles well above 90°, the curves have a negative slope, and stability can only be maintained with the aid of a high-speed regulator arranged to detect changes in reactive output, and hence of rotor angle. In the case of a machine directly connected to a substantially-constant-voltage busbar through a step-up transformer, a regulator energized from the machine terminals can detect changes in reactive output by virtue of the voltage drop it develops across the transformer impedance. A random increase in rotor angle raises the leading reactive output, which in turn depresses the machine terminal

Table 2

Stability-Limit Readings

Generator	Excitation control	Stator terminal readings: Voltage	Current	Power	Reactive power (leading)	Power factor (leading)	Rotor angle	Rotor current
		kV	amp	MW	MVAr		deg	amp
60 MW at Stella North S.C.R., 0·59	Hand	11·54	2180	14	41	0·32	92	105
	N	11·28	2330	16	42·2	0·35	97	128
	Hand	11·83	2310	31	34·5	0·67	72	225
	N	—	2450	31	36·7	0·64	79	220
	C	10·83	4120	29	69·9	0·38	138	275
	C	10·6	4800	46·4	74·8	0·53	128	426
	Hand	11·73	3600	61·4	38·4	0·85	78	420
	N	11·6	4020	60·2	52·5	0·75	95	420
	C	10·2	5600	59·6	80·4	0·59	131	580
100 MW, 13·8 kV S.C.R., 0·58	C	11·6	—	108	117–123	0·67	—	650–670
60 MW, 11·8 kV S.C.R., 0·63	Alternative C	10·25	4850	49·2	73·6	0·55	129	305
30 MW, 11·0 kV S.C.R., 0·52	Alternative C	H.V. busbar readings: 33	750	28·7	29·7	0·695	105	235

N. Normally inactive regulator.
C. Continuously acting regulator.

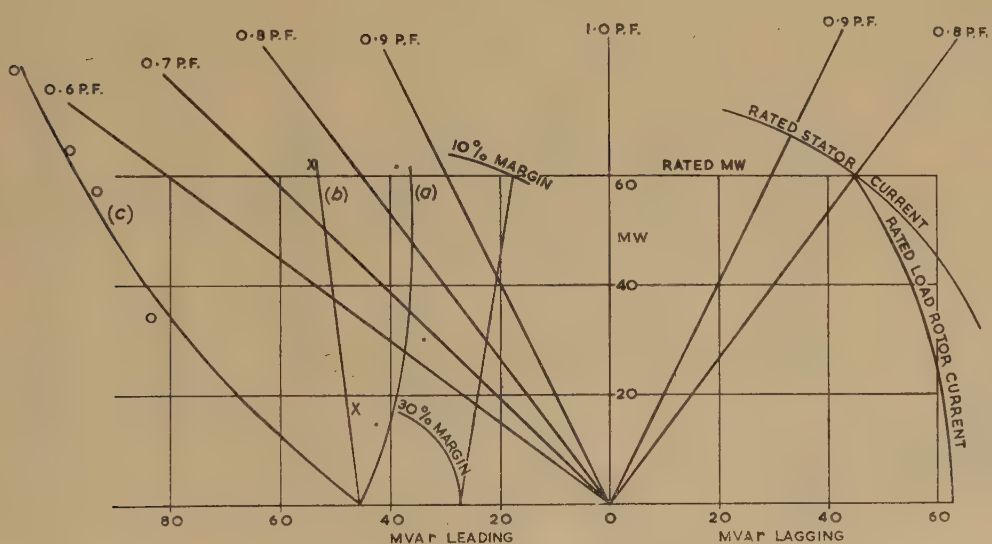

Fig. 1.—Generator power chart at rated voltage.

a) Hand control.
(*b*) Normally inactive regulator.
(*c*) Continuously acting regulator.

voltage. A regulator with no dead band thereupon increases the excitation to cause the output torque to exceed the driving torque and restore the rotor angle. The stability limit is exceeded when, owing to the increasing slope of the torque/rotor-angle curves, the time-constants of the rotor and main exciter, and the necessary damping of the regulator, the required changes in excitation cannot be made quickly enough to match the output and driving torques.

Fig. 2 also illustrates the effect of lowering the regulator setting on a fully loaded machine. If the operating point is initially at A, a reduction in excitation causes a momentary reduction in output torque and the point moves to E. The excess driving torque increases the rotor angle and leading reactive output until the machine voltage drops to the new regulator setting, and the operating point moves along the torque curve to the point B, (θ_1). At rotor angles greater than 90°, lowering the setting again momentarily reduces the excitation and output torque (point C). The excess driving torque accelerates the rotor along the reduced excitation curve to a point F, at which the leading reactive power is large enough to reduce the stator voltage below the new setting. If the automatic regulator has a sufficiently small dead-band and a sufficiently

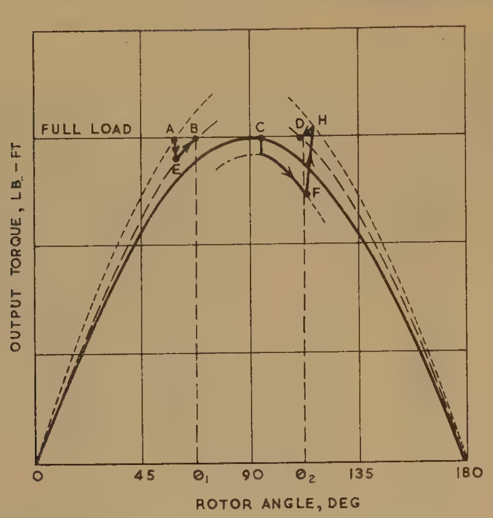

Fig. 2.—Output-torque/rotor-angle curves with different excitations.

·—·— Less than full-load minimum excitation.
——— Full-load minimum excitation.
- - - - / ...... } Higher excitations.

on open-circuit, but open-circuit figures were not included in the test programme, since the interest was in the overall response with the generator connected to the busbars. To check the overall response and also that stability was maintained when sudden excitation changes were made, a number of tests were taken, switching resistance into, or out of, the regulator-control circuit in order to reproduce the effect of step changes of stator voltage.

Table 3 gives typical instrument readings taken just before making step changes and after conditions had become steady. The initial rates of change, times and maximum reactive power were obtained from oscillograph records. In only one of these tests, the last column but one, was the regulator performance affected by operation of the reactive-power limiter.

The times, after initiation of the step change, to effect a change in the rotor voltage and the reactive power were approximately 0·2 and 0·4 sec for the normally inactive regulator, and approximately 0·14 and 0·25 sec for the continuously acting regulator. The tests show that, with the continuously acting regulator in particular, steady running can be maintained with sudden increases of leading reactive power causing large increases of rotor angle. The final rotor angle of 116° on one of the tests is of special note.

Table 3

STEP CHANGES IN REGULATOR REFERENCE VOLTAGE

Type of regulator		Normally inactive				Continuously acting		
Nominal step change, % ..		−3	+7	+7	−7	+3	−7	−7
Stator, kV	Start	12·1	12·08	11·9	11·91	11·68	12·06	11·68
	Finish	11·72	12·8	12·7	11·2	12·05	11·8	10·6
Stator, amp	Start	1 460	1 640	3 000	3 020	3 400	3 280	3 440
	Finish	1 720	1 640	3 430	3 450	3 040	3 600	4 920
Stator, MVAr	Start	0·8 (*a*)	13·3 (*b*)	8·3 (*a*)	5·8 (*a*)	31·3 (*b*)	31·9 (*b*)	31·9 (*b*)
	Finish	15·6 (*b*)	18·7 (*a*)	45·8 (*a*)	25·4 (*b*)	18·0 (*b*)	41·3 (*b*)	65·1 (*b*)
Stator, MW	Start	30·4	30·6	60·6	60·6	60·4	59·6	61·0
	Finish	30·0	30·2	60·0	61·8	60·4	60·0	61·4
Rotor angle referred to stator terminals, deg	Start	31·5	48	46	47	80	76	77
	Finish	50	23	25	73	63	87	116
Rotor, amp	Start	385	305	565	550	410	415	420
	Finish	280	520	795	465	480	410	540
Rotor, volts	Start	95	75	148	145	103	104	105
	Finish	70	132	213	121	121	103	135
Initial change } Rotor, volts/s ..		65	55	60	—	560	800	900
Initial change } MVAr/s ..		7	5·3	10·5	16·5	4·5	11·5	Reactive
Maximum reactive power, MVAr ..		15·6 (*b*)	18·7 (*a*)	46·0 (*a*)	33·0 (*b*)	18·0 (*b*)	48 (*b*)	power
Time to reach maximum reactive power, sec ..		29	18	16	4	6·5	1·8	chart
Time to reach ±5% of final reactive power, sec		25	15	11	21	5·5	4·4	stopped

(*a*) lagging. (*b*) leading.

high response, it increases the excitation to a point H, where there is an excess output torque, the rotor angle is reduced and steady operation obtained at point D, (θ^2). If the regulator does not increase the excitation fast enough, the rotor angle continues to increase and instability occurs.

(3.3) Automatic-Regulator Response Tests

The July series of tests on the continuously acting regulator showed that the regulator damping required modification to give optimum results under generator load conditions, and for the October test series the best damping compromise between open-circuit and load conditions was obtained. The regulator manufacturer took some commissioning figures with the generator

(3.4) Reactive-Power-Limiter Tests

In order to determine the effect of operation of the leading-reactive-power limiter, step changes were made in the automatic-regulator control circuit to reduce excitation. The results of two typical tests are shown in Figs. 3 and 4. Fig. 3 is for a 7% step change with a normally inactive regulator controlling excitation, and Fig. 4 is for a 10% change using a continuously acting regulator. Identical initial conditions and step changes were not essential, since a close comparison of the two regulators was not intended. Their responses are, in any case, very different.

The exciter-field voltage was not recorded for the test shown in Fig. 3. The time to change the rotor voltage was 0·2 sec

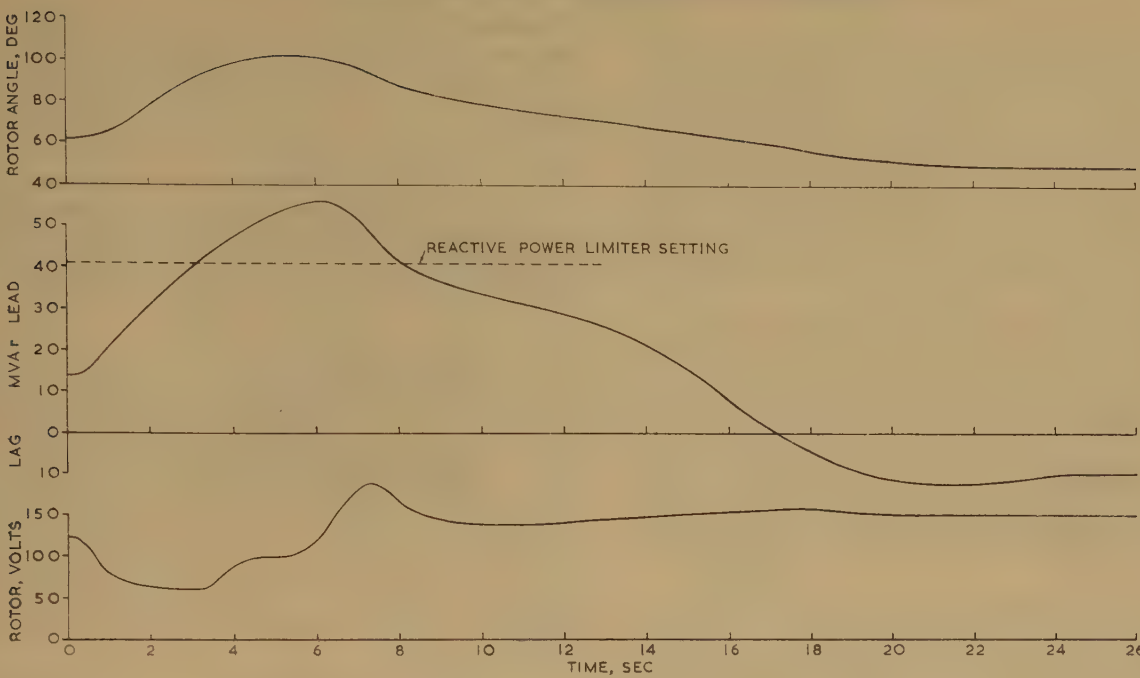

Fig. 3.—Normally-inactive-regulator reactive-power limiter test.

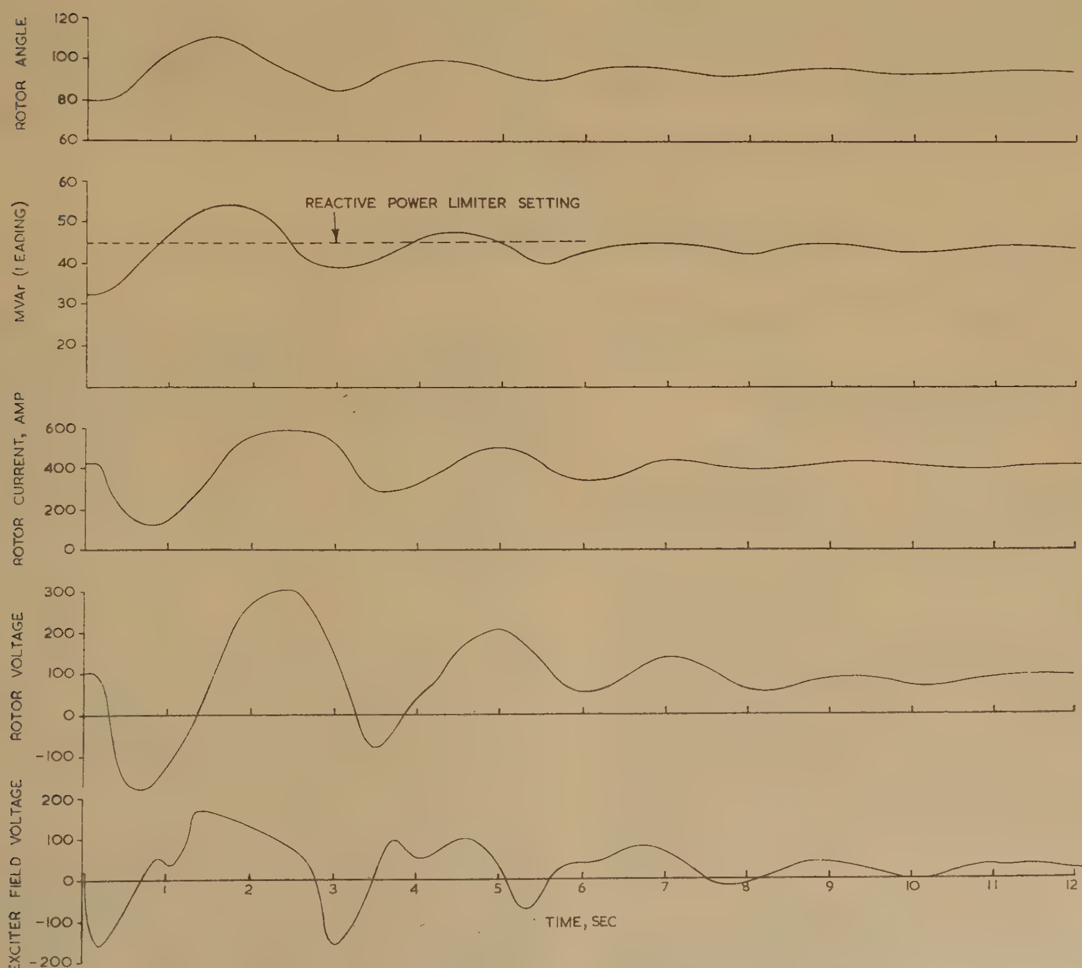

Fig. 4.—Continuously-acting-regulator reactive-power limiter test.

with an initial rate of change of 60 volts/sec, and the rate of change of reactive power up to the maximum value obtained was 7 MVAr/s. After making the step change in the test shown in Fig. 4, the times to affect the exciter-field voltage and the rotor voltage were 0·06 sec and 0·14 sec. The initial rate of change of rotor voltage was 1 000 volts/sec, and the rate of change of reactive power up to the maximum value obtained was 14·5 MVAr/s. It is to be noted that the rotor voltage changes polarity, and, while the rotor current is considerably reduced, it does not change direction, owing to the inductance of the winding.

Although the limiter for the normally-inactive regulator was set within 4 MVAr of the theoretical stability limit, synchronism was maintained. However, the excitation was increased too much after the operation of the limiter, resulting ultimately in a change to a slightly lagging power factor. The degree of excitation increase is a matter of adjustment, and other cases of over-correction in this respect have occurred. The adjustment requires special attention during commissioning: for the continuously acting regulator the final reactive load was very close to the reactive-power setting.

(3.5) Effect of a Sudden Change of System Impedance

By switching in or out an external impedance in the form of two 132/275 kV auto-transformers, some further assessment of transient system changes was obtained. The two transformers were local to the generator and its step-up transformer, i.e. there was no appreciable length of line included. The transformers were connected in series and their combined impedance was 25% on a 100 MVA basis. Two typical sets of results obtained before and after switching, using the continuously acting regulator, are given in Table 4.

Table 4

SUDDEN CHANGE OF SYSTEM IMPEDANCE

Test conditions	Stage of test	Stator terminal readings						Rotor
		Voltage	Current	Reactive power (leading)	Power	Power factor (leading)	Rotor angle	
		kV	amp	MVAr	MW		degree	amp
Increasing external impedance ..	Start	12·3	3 120	28·0	59	0·90	69	420
	Finish	12·2	2 944	8·3	60·4	0·99	64	505
Reducing external impedance ..	Start	10·98	3 520	26·6	61·0	0·92	89	435
	Finish	10·88	5 420	75·9	61·0	0·63	123	520

It might be considered that inserting an inductive impedance would tend to produce instability. Initially it does, but with constant system voltage and the automatic regulator connected to the machine terminals, the addition of inductive impedance at first reduces the generator voltage under leading-power-factor conditions, the excitation is immediately increased and thus the leading reactive power is less than before the change. At lagging power factors the reverse occurs: the automatic regulator reduces excitation and finally the lagging reactive power is reduced.

(3.6) Stator-Core End Heating

At times of light load on the transmission system, there will be increasing use in the future of certain turbo-generators at leading power factors. The comparatively recent improvements in automatic-regulator control make such operation possible from the point of view of steady-state stability, but the possibility of stator-core end heating becoming a limiting factor has to be examined. Some aspects of this problem have been dealt with recently,[3] but such operating limits for machines of modern design have not been established.

Stator-core end heating tests on load at various leading power factors were taken at Stella North power station and also on another 60 MW machine at Marchwood power station, near Southampton. A comparison was made between the effect of magnetic and non-magnetic end-rings on stator-core end heating.

(3.6.1) General Considerations.

The leakage flux cutting the solid heavy-section clamping plates at the ends of the stator core produces eddy currents and heating. The flux in any particular machine is a function of the rotor and stator currents and the relative positions of their respective fields, as determined by the operating power factor. When comparing different machines, the use of magnetic or non-magnetic material for the rotor end-rings and stator-core clamp plates also affects the resultant leakage flux. The tests discussed below were taken on two 60 MW machines, and both had a short-circuit ratio of approximately 0·6. They were, however, of different manufacture and had certain detailed design differences.

(3.6.2) Heating Comparison with Different End-Ring Materials.

Temperature runs, for a range of power factors at constant stator current and approximately constant stator voltage, were taken on the Stella generator, first with non-magnetic rotor end-rings and, some months later, with magnetic rings. The temperatures were measured by 15 thermocouples, built into the machine in the first ventilation duct, on the tooth support and on the clamp-plate, at the turbine end of the generator. At the point of measurement, the thermocouples were covered with wood packing-pieces to shield them from the direct cooling of the hydrogen. Steady temperatures were reached after heat runs of about 30 min. The maximum temperature rises were obtained in the first ventilation duct and these are shown in Fig. 5. The pressure of the hydrogen was between 0·5 and 1·0 lb/in^2 (gauge).

The tests are particularly useful in comparing the effects of the two end-ring materials, since the thermocouples were in identical positions for the two series of tests. The temperature rises with magnetic end-rings are about twice those with the non-magnetic ones, and, based on these results, it is calculated that at rated load and 0·9 power factor, leading, the maximum temperature rises would be 66° C and 31° C, respectively.

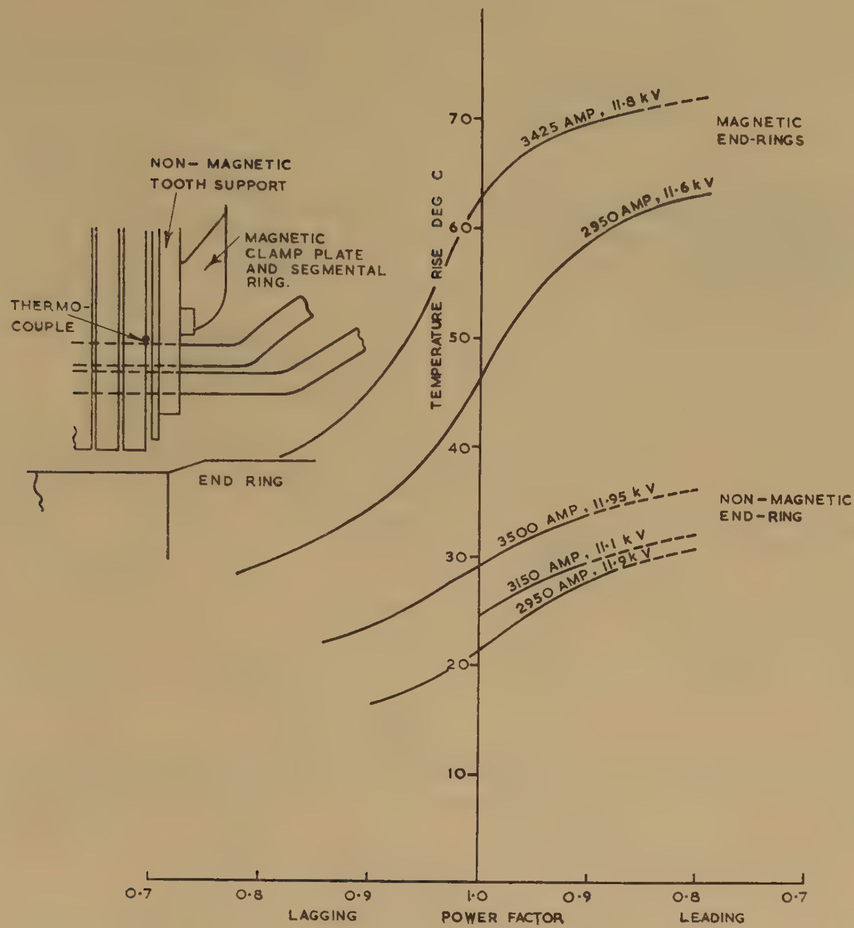

Fig. 5.—Core-end heating with magnetic and non-magnetic end-rings.

(3.6.3) Variation of Stator Currents and Gas Pressures.

A further series of tests taken at Marchwood power station, on a 60 MW machine with non-magnetic stator clamp-plates and rotor end-rings is illustrated in Fig. 6. In this case also, the thermocouples were placed in position during the building of the stator. Thermocouple A, for instance, was embedded between the clamp-plate and the first packet of punchings. Again the hottest positions were found to be near the bottom of the slot. These tests illustrate that the highest temperatures are in the immediate vicinity of the clamp-plate, and that it is important to take measurements well away from the ventilated surfaces to obtain a true picture of the maximum temperature conditions.

The results obtained over the fairly wide range of stator currents enable an assessment to be made of the effect on core end heating of varying the stator currents. The results show that at leading power factors the temperature rise is proportional to $(\text{current})^{1\cdot2}$ for gas pressures of the order of $4\,\text{lb/in}^2$ (gauge).

Core-end temperature rises at leading power factors over a range of hydrogen pressures with constant stator currents were also obtained, and some of these results with an extrapolation up to $50\,\text{lb/in}^2$ (gauge) H_2 are given in Fig. 7, curve (*a*). Curve (*b*) is taken from a paper by Estcourt *et al.*[4] for what is believed to be a machine of relatively high short-circuit ratio with magnetic end-rings. The lower reduction in temperature rise with higher gas pressures can be accounted for if the stator-core end-plates have a cooling surface relatively smaller than that of the Marchwood machine.

(4) ASYNCHRONOUS OPERATION

(4.1) Introduction

A turbo-generator with no field excitation may be operated as an induction or asynchronous generator, its output being dependent upon the amount by which the rotor speed exceeds the synchronous speed, i.e. the slip. Perhaps the earliest asynchronous-running tests were those which took place in 1951 at Little Barford power station. It was found that, because of the small slip at which full power output could be obtained, there was little danger of over-heating the rotor, but on the other hand, the large magnetizing current taken from the system led to overloading the stator. In a recent paper[3] the possibilities of large solid-rotor asynchronous generators were reviewed, but there does not yet appear to be a place for these machines.

Two classes of asynchronous torques may be distinguished, depending upon whether they arise because a machine is oscillating about a steady synchronous position, or because it is slipping through one or many pole pitches. These will be identified by the terms 'damping torque' and 'asynchronous torque', but each may be related to the other. The damping torques may be important in determining the correct design of high-speed voltage regulators and sensitive steam-governing systems. The asynchronous torques are important when con-

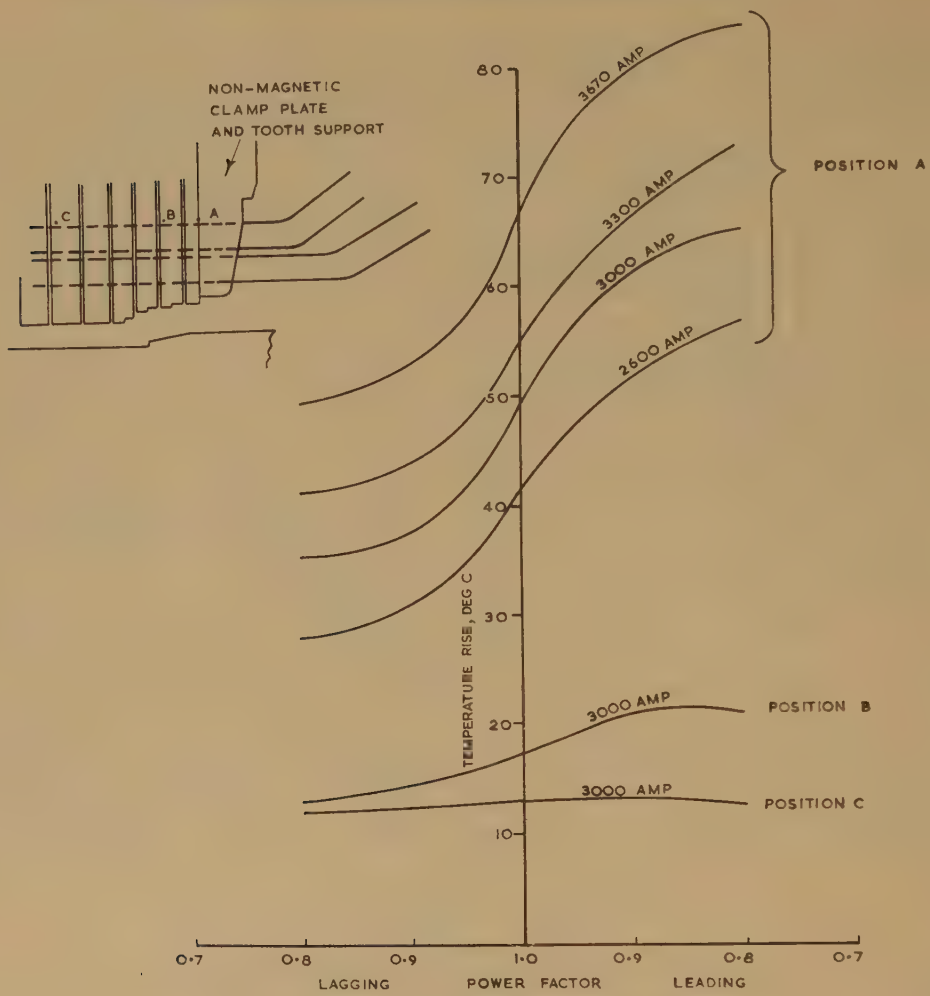

Fig. 6.—Core-end heating at various stator currents.
Pressure, 3·8 lb/in² (gauge) H_2.

sidering the operation of machines with no field excitation, out-of-step and resynchronizing performance, and self-synchronizing performance.

(4.2) Asynchronous Tests

The machine was first run synchronously at constant load with the field current adjusted to give an output power factor of about unity. The field breaker was then tripped, and when the field flux had decayed sufficiently and the machine speed had risen to a more or less steady value of slip, readings were taken of various quantities, notably power output and slip frequency. After a half to one minute the field breaker was reclosed manually, and with the resynchronizing of the set the test was concluded. The results of the tests are shown in Figs. 8, 9 and 10.

In each test series, asynchronous characteristics were found for two tap positions of the generator step-up transformer. Because of the very small slip, the power output may be taken as representing the torque with reasonable accuracy. In one set of tests, the field circuit was connected through the field-discharge resistor, and in another the field was open-circuited. In the first case, there were marked oscillations at twice the slip frequency in the amplitudes of the currents and voltages in the stator and field circuits, and in the asynchronous active and reactive power outputs. The power/slip curves shown in Figs. 8 and 9 are based on the values of average power and slip as the most practical criterion of performance. If the results shown in Fig. 9 for a number of turbo-generators tested in this country had been plotted on a per-unit instead of a megawatt basis for the power, the resulting curves would have been grouped very closely together.

(4.3) Power/Slip Characteristics and Damping Constants

(4.3.1) The Peak of the Power/Slip Curve.

The power/slip curves for a turbo-generator shown in Fig. 8 have a form similar to those for induction motors. Up to slip velocities of the order of 0·5% the curve is almost linear; it then flattens out and reaches a maximum between 0·5% and 1·0% slip. This value will depend upon system conditions, i.e. on generator-transformer tap position, system voltage and impedance. Prior to the tests at Stella North, this maximum was expected to exist, but, as far as is known, it had not been found experimentally (or theoretically) for turbo-generators. In a set of asynchronous tests with the generator transformer at tap 5, a test was taken at 44 MW, and a slip of 0·41% was obtained. The generator was then operated at 60 MW, and, when the field breaker was tripped, the machine reached a steady slip of about 2·85% and the governor responded, reducing the power output to about 38 MW. Thus the generator was operating beyond the peak of the power/slip curve, and the peak value must lie between 44 MW and 60 MW.

The ratio between the curves for tap 15 and tap 5 is about

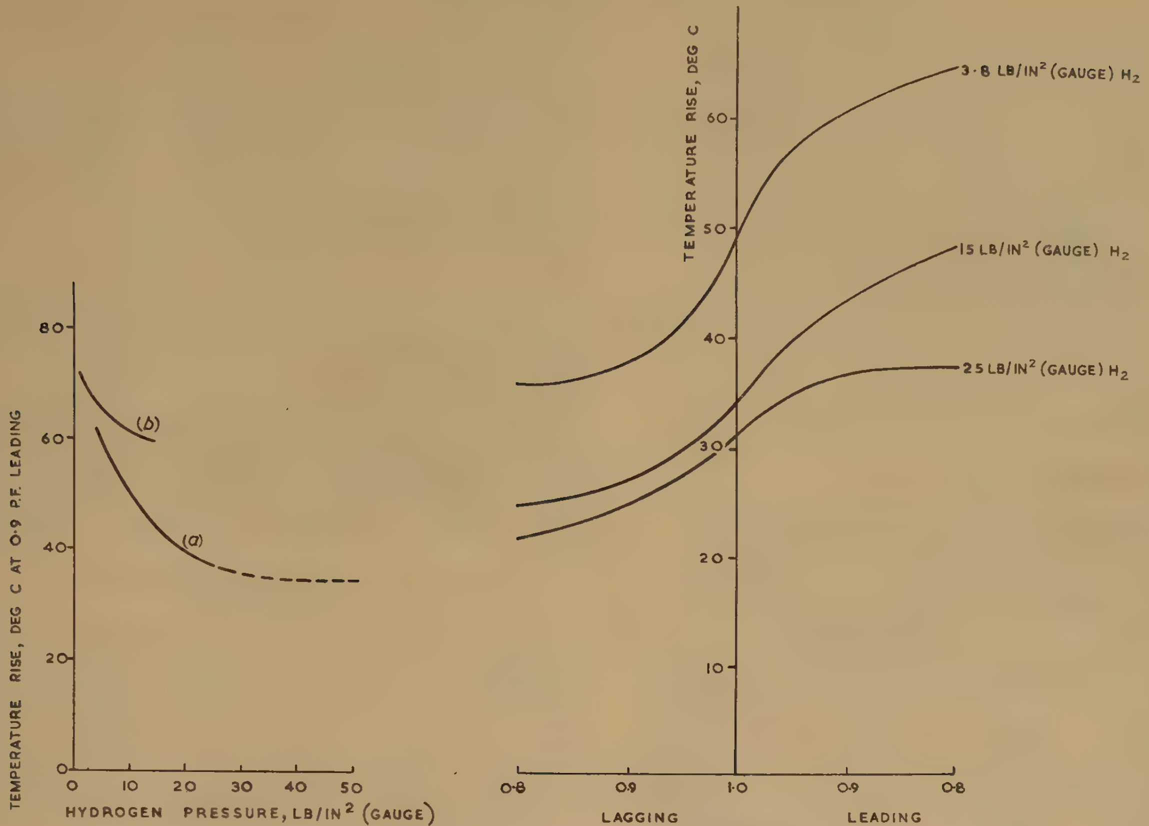

Fig. 7.—End heating related to hydrogen pressure.

Constant current of 3 000 amp.
(*a*) Marchwood test.
(*b*) American results[4] (4 700 amp).

1·5 : 1, and the peak could thus be expected to be between 66 and 90 MW for the tap 15 case. It is likely that only at the lower slips would appreciable torques arise from the field, and therefore that curve (*d*) in Fig. 8 lies close to curve (*b*) in the region above 1·5% slip.

(4.3.2) Effect of Generator-Transformer Ratio and Field-Circuit Connections.

The two groups of power/slip curves in Fig. 8 indicate the effect of the generator-transformer ratio. At Stella North, as at many power stations, the busbar voltage is normally high and the generator-transformer ratio is normally about tap 5. Consequently, when the field is lost, conditions approximate to those represented by curve (*b*) of Fig. 8, and the machine will operate beyond the peak of the power/slip curve.

The contribution made by the field winding to the total asynchronous torque, whose magnitude consists of a constant and an oscillatory component, depends upon the connections of the field. It is likely to be a maximum when the field is short-circuited and will be zero when the field is open-circuited. With the field-discharge resistor connected, there is a stator-current variation of from about 5 to 15%, depending upon the power output and generator-transformer tap position, but this falls to 2 or 3% when the field is open-circuited, owing to the small difference in the geometry of the rotor in the direct and quadrature axes.

(4.3.3) The Damping-Torque Coefficient for Small Oscillations.

There is a close relationship between the damping-torque coefficient for small oscillations and the torque/slip charac-

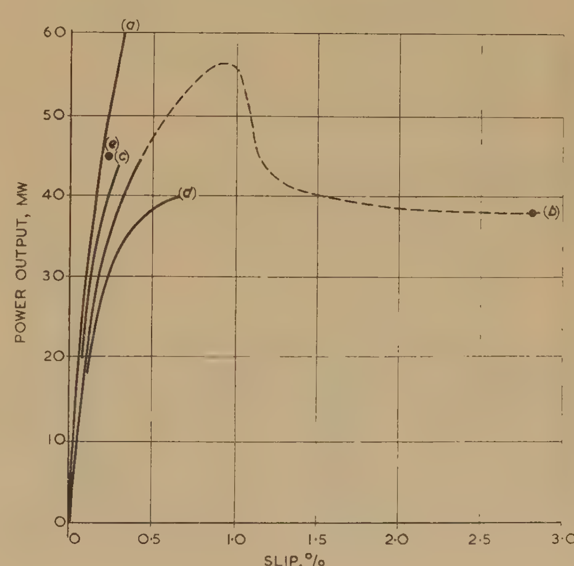

Fig. 8.—Power/slip characteristic of 60 MW turbo-generator.

(*a*) Tap 15 with field discharge resistor.
(*b*) Tap 5 with field discharge resistor.
(*c*) Tap 15 without field discharge resistor.
(*d*) Tap 5 without field discharge resistor.
(*e*) Tap 15 with field discharge resistor, and non-magnetic rotor end-rings.

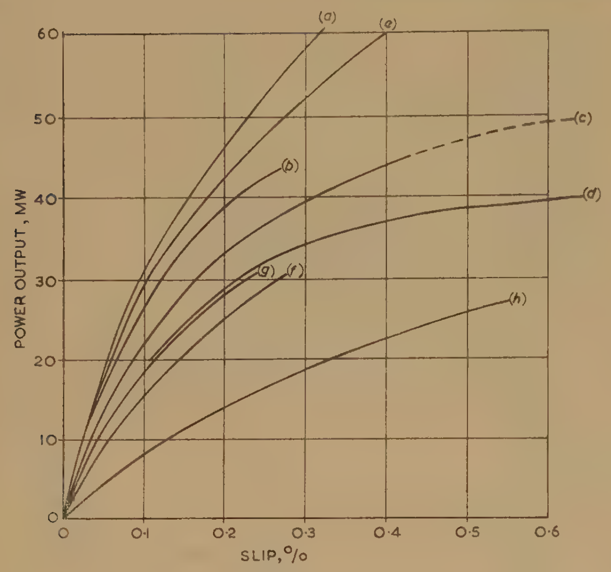

Fig. 9.—Power-slip characteristics of turbo-generators.

	Rating	Approximate nominal busbar voltage per cent (including effect of generator transformer ratio)	Field circuit connection
(*a*) Stella North	60 MW	105	With discharge resistor
(*b*) Stella North	60 MW	105	Open-circuited
(*c*) Stella North	60 MW	92	With discharge resistor
(*d*) Stella North	60 MW	92	Open-circuited
(*e*) Marchwood	60 MW	105	With discharge resistor
(*f*) Cliff Quay [10]	45 MW	92	Open-circuited
(*g*) Little Barford ..	30 MW	94	Short-circuited
(*h*) Little Barford ..	30 MW	94	Open-circuited

coefficient, T_d, may be derived from τ_d, and the synchronizing-torque coefficient, T_s, from T_d and f_0, the simple analysis leading to a second-order differential equation.[5]

Thus in Table 5, T_d and f_0 are experimental results from which T_s is derived, and s and P_a are derived from T_d and f_0, assuming the equivalence of the asynchronous- and damping-torque coefficients. Hence the slip $s = f_0/f \times 100\%$, where f is the system frequency, and the asynchronous power

$$P_a = T_d(f_0/f) \times 75\,\text{MW}.$$

If the values of s and P_a are plotted on Fig. 8, it will be observed that they fall below the power/slip characteristic; this probably arises from the effect of field excitation in increasing iron saturation, as mentioned above. The results in Table 5 show clearly the effect of a high-speed voltage regulator in providing a higher synchronizing-torque coefficient, and thus a higher frequency of oscillation, than where the machine was under hand-control. The last two lines show the effect of increased external impedance in reducing the damping- and synchronizing-torque coefficients and the natural frequency of oscillation, f_0.

(4.4) Limit of Operation without Field

(4.4.1) Rotor Currents and Heating.

The approximate average rotor losses are given in Fig. 10 as a function of the average asynchronous output. These values were obtained by multiplying the sum of average active power output and average stator I^2R loss by average slip. The curves show the effect on rotor losses of generator-transformer tap position, and the connection of the field. Thus in curves (*f*) and (*g*), not only are the losses greater, but they arise exclusively in the rotor surface, end-rings and damping bars, since the field is open-circuited. However, from examination of the rotor, it

Table 5

Oscillating Frequencies and Damping-Torque Coefficients

Test condition	Field control	Generator-transformer tap	Damping-torque coefficient, T_d	Frequency, f_0	Synchronizing-torque coefficient, T_s	Slip, s	Asynchronous power, P_a
			per unit	c/s	per unit	%	MW
Resynchronizing after slipping one pole pair ..	C	15	19·2	1·4	2·27	2·8	40
Failing to resynchronize after slipping one pole pair	Hand	5	18·2	0·95	1·08	1·9	26
Resynchronizing after slipping two pole pairs ..	Hand	5	16·7	0·97	1·13	1·94	24
Switching-in high-impedance link to system ..	C	15	9·7	1·11	1·4	2·22	16
Short-circuiting high-impedance link to system..	C	15	21·2	1·39	2·26	2·78	44

C. Continuously acting regulator.

teristic. If the effect of the transient saliency of the machine and the variation in slip can be neglected, the damping-torque coefficients obtained from the analysis of small oscillations and from the torque/slip curve should correspond. There may be differences due to iron saturation, because, if the machine has field excitation applied, the flux density in the rotor teeth will be higher than if the machine is running asynchronously and is only excited from the system. This increased iron saturation will produce greater skin effect in the rotor, increased equivalent rotor resistances and smaller damping torques. In the second series of tests, accurate rotor-angle measurements were obtained by stroboscopic means, and in a number of cases damped oscillations were recorded. A number of these have been analysed to find the time-constants, τ_d, with which these oscillations die away and their frequencies, f_0. The damping-torque

appeared that losses up to 1 000 kW, obtained on test and maintained for about 30 sec, did not cause any appreciable rotor damage.

The field-discharge resistor at Stella, which is designed to carry 875 amp for 10 sec, showed no signs of distress during the tests. This is not surprising, because the average field current during asynchronous running never exceeded 100 amp: the field-breaker auxiliary contacts would carry such a moderate current indefinitely without overheating.

(4.4.2) Stator Currents and Heating.

The stator currents obtained during asynchronous operation are shown in Fig. 10. This indicates a limit for continuous operation at about 33 MW for tap 5 and 36 MW for tap 15. This limit of operation at about half load, due to the magnitude

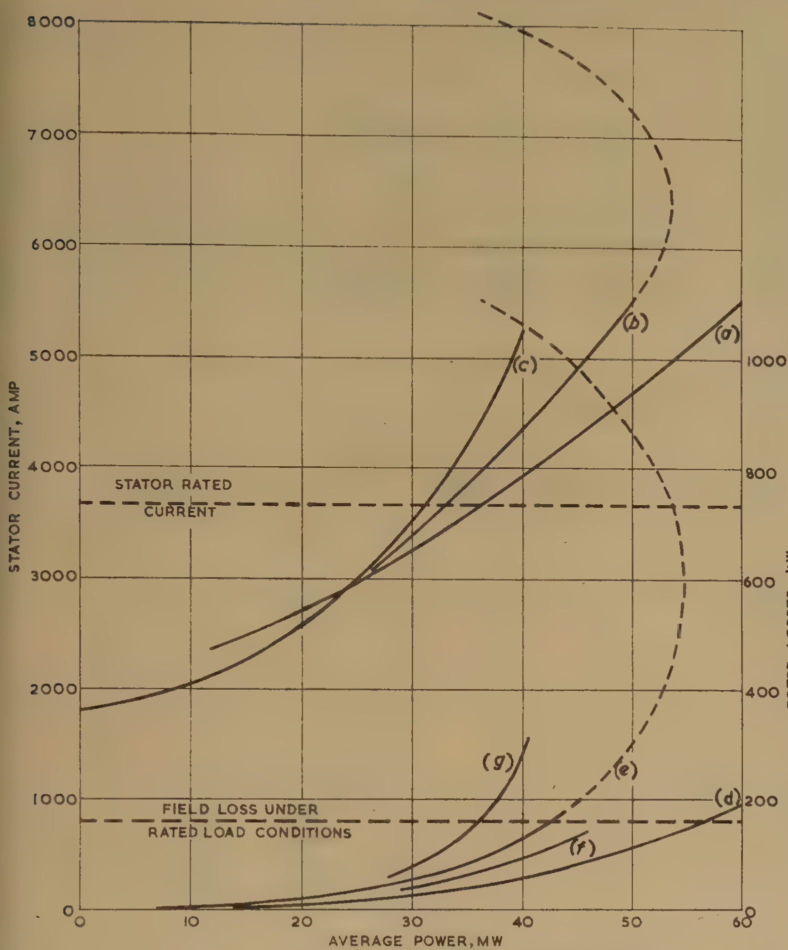

Fig. 10.—Stator current and rotor losses in asynchronous tests.

(*a*) Current with field discharge resistor connected (tap 15).
(*b*) Current with field discharge resistor connected (tap 5)
(*c*) Current with no field discharge resistor connected (tap 5).
(*d*) Rotor losses with field discharge resistor connected (tap 15).
(*e*) Rotor losses with field discharge resistor connected (tap 5).
(*f*) Rotor losses with no field discharge resistor connected (tap 15).
(*g*) Rotor losses with no field discharge resistor connected (tap 5).

of the stator current, was also found for all machines listed in Fig. 9. The increased heating, occurring in the end of the stator core when the leading currents, arising from asynchronous operation, are flowing, might lead to the need for an even lower operating limit. This did not appear to arise with the Stella generator, even when fitted with magnetic end-rings, but sufficiently long-term asynchronous-running tests were not carried out to establish this with certainty. If operation is attempted with greater than the rated stator current, it is likely that the generator transformer will prove to be the most sensitive to overload, and the winding temperature protection may operate.

(5) OUT-OF-STEP AND RESYNCHRONIZING TESTS

(5.1) Introduction

Power-system operators often consider that when a generator loses synchronism it should be isolated from the system, and power-system designers aim to make such an occurrence infrequent by careful design. Apart from one study,[5] little attention seems to have been given in this country to the possibility of a machine, having lost synchronism, regaining it either spontaneously or by the intervention of an operator or automatic equipment.

In a number of cases during the test series the generator lost synchronism, but on every occasion it was possible to bring the machine back into step; these incidents are examined below to establish the criterion for resynchronizing.

(5.2) Test Procedure and Results

The unit operated out of step, without this being directly intended, at the conclusion of some steady-state-stability and asynchronous-running tests. There were also some out-of-step running tests in which the machine was run at a constant output of about 30MW, and the field excitation adjusted to the steady-state stability-limit value. The field excitation was reduced

Table 6

Out-of-Step Operation

Reference No.	Test condition	Output with synchronism		Out-of-step operation			
		just lost	just regained	Stator current: Maximum	Stator current: Minimum	Pole-pairs slipped	Duration
		MW	MW	per unit	per unit	No.	sec
51A	Steady-state stability with long line and no regulator ..	60·6	50	2·7	0·3	47	29
135B	After asynchronous operation on tap 5. (No regulator)	61	55	3·2	1·1	43	31
158	After asynchronous operation on tap 5. (No regulator)	45	44·6	2·2	0·97	2	11
144A	Steady-state stability with continuously acting regulator..	47	47	2·2	0·48	1	5
	Out-of-step						
153A	Field current, 50A	30	31	1·1	0·73	1	32
154A	Field current, 100A	30·6	31	1·26	0·74	1	36
154B	Field current, 150A	31	31	1·20	0·70	1	44
167	Out-of-step with continuously acting regulator	59	59	3·7	1·55	{ 4 3	5 4

to a known value (obtained by previously calibrating the exciter-field rheostat) and the machine then ran out of step. At 30 MW, the stability limit was found to be with a field current of about 200 amp. Three out-of-step tests at this load were carried out with field-rheostat settings corresponding to 50, 100 and 150 amp.

Some of the results of these tests are given in Table 6, together with other tests at Stella in which pole-slipping occurred. In tests 153A, 154A, 154B and 167 there was a deliberate attempt to run the generator out of step; in the other tests this was incidental to their main purpose. Curves derived from oscillograph records are given in some detail in Fig. 11 for test 167. In this test the machine was operated at about full load with the continuously acting voltage regulator in service, and the field excitation was weakened until the machine lost synchronism. It then slipped four pole pairs, very nearly resynchronized, and slipped a further three pole pairs before the regulator setting was increased sufficiently to ensure synchronism.

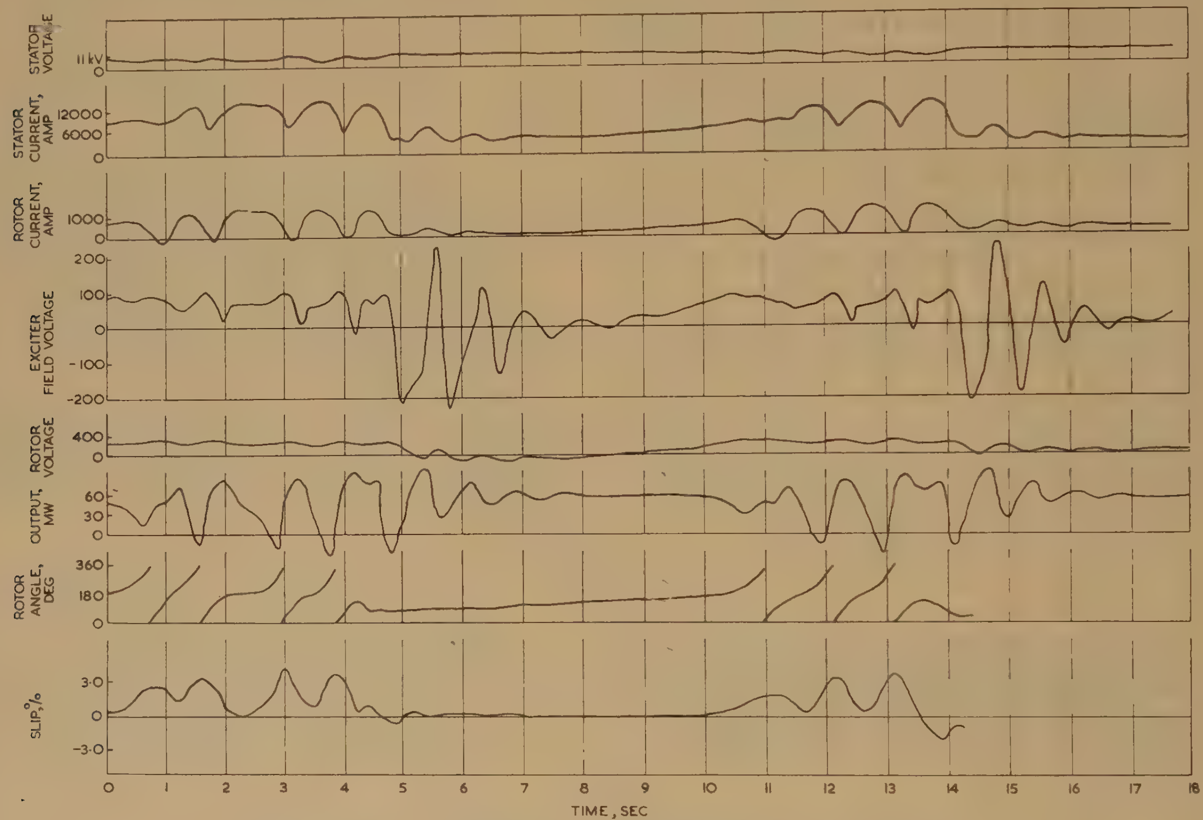

Fig. 11.—Out-of-step operation with continuously acting regulator (test 167).

(5.3) Operational Limits and Resynchronizing Procedure

The severity of conditions when operating out of step depends —as for asynchronous running—on whether or not the slip is such that operation is beyond the peak of the asynchronous power/slip curve. Beyond this peak, resynchronizing is difficult and can be achieved only if the power output is reduced.

This is indicated in Table 6 by the results for tests 51A and 135B. In the first case, the peak of the power/slip curve was reduced below 60 MW because of the high external impedance, and in the second because of the low generator voltage arising from the generator-transformer tap position. In both cases the steam supply to the turbine had to be reduced before the generator would resynchronize, even with maximum field excitation.

(5.3.1) Criteria for Resynchronizing.

A definite relationship can be established[6] between the field excitation for resynchronizing at a particular load and the effective damping torques of a machine, subject to certain simplifying assumptions. If the damping-torque coefficient exceeds a critical value, the generator will just resynchronize for a field excitation corresponding to that for the steady-state stability limit. Thus the generator can operate out of step only when the excitation is below this value, and this gives a definite limit to the magnitude of the stator currents. The damping-torque coefficient does exceed the critical value for the Stella generator in the region up to about 0·5% slip, corresponding to an output of about 50 MW. The extent of this region will be influenced by the equivalent-system impedance and generator-transformer tap position, as already discussed in Section 4.3.3. Beyond this region, resynchronizing can be obtained only by a reduction in the power output. The resynchronizing performance based on three different assumptions is illustrated by Fig. 12, where the resynchronizing region is above and to the left of the various curves. The approximation for the asynchronous characteristic used for curve (*b*) gives a maximum resynchronizing power of 49 MW, which is in reasonable agreement with the results for tests 51A and 135B given in Table 6. For curve (*c*), based upon a linear characteristic, the machine is critically damped, and, provided that the field is adequate

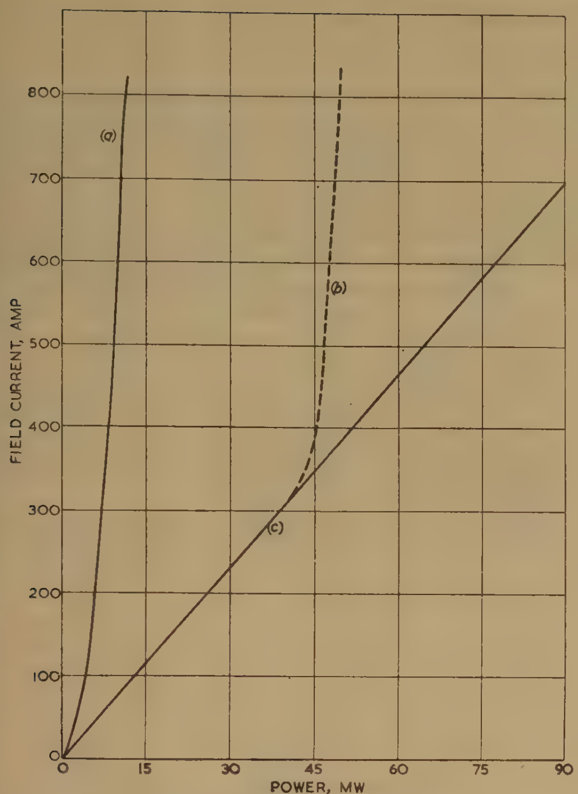

Fig. 12.—Resynchronizing limits.

(a) Resynchronizing line, $T_d = 5 \cdot 0$.
(b) Resynchronizing line, $T_d = 5 \cdot 0 + 38$ MW constant.
(c) Resynchronizing line, $T_d = 150$ (also theoretical steady-state stability limit).

to maintain steady-state stability, the machine will ultimately resynchronize. This last case corresponds to the remaining tests shown in Table 6.

(5.3.2) Stator and Rotor Heating when Out of Step.

It is shown in Table 6 that the stator currents are largest when the slip is high—as in the asynchronous tests—and particularly when the continuously acting voltage regulator is in service. The observations made in Section 4 apply in this case, but with added force, because both the stator and rotor currents are larger. It appears from the waveform of the stator-current envelope, shown in Fig. 11, that the heating effect will approximate to that of a steady current of the maximum value recorded. The induced rotor current will be large with large slips, and the field-excitation current will provide an additional source of heat. The rotor was withdrawn for inspection after the July tests, and slight blueing of the rotor end-rings was observed. The discoloration is thought to have occurred in tests 51A and 135B (when the pole-slipping was preceded by 30 sec of asynchronous running at a slip of 2·85%), and conditions must then have been close to the limit for safe continued operation.

(5.3.3) Performance of Governor and Automatic Boiler-Control Equipment.

The steady-state characteristic of the governor at full load is such that a 4% rise in speed will lead to complete shutting of the main steam valves. This would be equivalent to a damping factor of 25 but for the time lags in the governor system which reduce the effective value of this damping factor, or even make it negative. There is, for example, evidence to show, from records of valve opening during test 135B, that the governing system had no positive effect in achieving resynchronizing.

In test 51A a resynchronizing power of 50 MW is given. In fact, just as the generator resynchronized after slipping 47 poles, the unit-boiler safety valve blew off, and, shortly afterwards, due to excessive reaction by the automatic boiler-control equipment, boiler ignition was lost. The output of the generator then fell slowly to about 3 MW, ignition was regained and the output increased to about 50 MW in five to seven minutes.

(5.3.4) Voltage-Regulator Action.

The oscillographic records of test 167, given in Fig. 11, indicate the effect of a continuously acting voltage regulator on the performance of a generator when out of step. There are violent oscillations in the exciter-field voltage, and the stator currents are made very large. The regulator attempts to increase excitation when the terminal voltage is a minimum, i.e. when the generator is 180° out of phase, and to reduce it when the generator is in step. There are inevitable delays due to the exciter and rotor time-constants, and the effect of regulator action on the power output will depend upon the time taken by the rotor to slip through 360°. In this case, the average time was about 1¼ sec, and it would seem that the regulator would have a small positive effect in reducing the slip of the generator. At higher frequencies of slip it would be likely to have an unfavourable effect.

(5.4) Protection

The generator tested is fitted with an inverse definite-minimum-time back-up overcurrent relay having a current setting range of 50–200% of 1 amp. The relay is energized direct from three current transformers, of ratio 300/1, connected in series with the generator 132 kV circuit-breaker. The normal settings of the relay are 175% and 0·66 time multiplier, but during the tests the current setting was raised to 400% to avoid undesired operation under extreme conditions.

Tests on the relay in question and calculations show that, with normal settings, the relay would have operated and tripped the machine 132 kV breaker after between 9 and 28 sec under the various pole-slipping conditions experienced at full load, and after 22 sec with loss of field at full load and a slip of 2·85%. Due to the timing tolerances permitted by B.S. 142, operation of standard relays of the type mentioned is uncertain under these running conditions, but definite operation after between 6 and 24 sec would be assured if the current setting were reduced to 150%. This solution has the objection that, with loss of field at full load, the operator has only about half as much time in which to prevent relay operation by reducing load. Also, relay operation on 132 kV earth faults, external to the generator circuit, becomes appreciably faster than is necessary to safeguard the rotor against overheating by negative-phase-sequence current in the stator.

(6) SELF-SYNCHRONIZING OF TURBO-GENERATORS

(6.1) Introduction

A new method,[7,8] here termed self-synchronizing, of connecting a generator to the system appears to have been adopted quite widely in Eastern Europe. The procedure is to run the generator to within a few per cent of synchronous speed and then to connect it to the system by closing the main breaker, prior to energizing the field. The field breaker may then be closed automatically by means of an auxiliary contact on the main breaker, or closure may be delayed until the slip of the rotor has reached a small value.

The self-synchronizing process can be considered in three parts. First, there is the magnetizing period immediately after the main breaker has closed. The peak value of current will occur in the first cycle or two, and d.c. and sub-transient a.c.

components will have become negligible within the first 5 cycles. Secondly, there is the asynchronous-running period when the asynchronous torques and governor action will bring the generator speed close to the synchronous value. Thirdly, there is the synchronizing period from the time when the field switch is closed to that when synchronism is reached. The last two periods will not be distinct if the field breaker is closed immediately after the main breaker. In the tests carried out at Stella, the closure of the field breaker was deliberately delayed so that the different phenomena could be distinguished.

(6.2) Test Procedure and Results

The generator was run at the required speed with both main and field breakers open and the exciter-field rheostat set to give no-load excitation. The main breaker was closed first, followed by the field breaker after an interval of between 4 and 17 sec. The generator speeds were adjusted to give a range of slips from −2·8 to 0·77%.

The results obtained in the eight tests taken are given in Table 7. It is seen that the maximum peak currents in the stator and in the 132 kV circuit-breaker were obtained in test 152, and were respectively 4·52 and 5·6 times full-load. Closure of the main breaker did not give rise to any noticeable voltage dip.

Oscillogram and recorder traces for test 150 are reproduced as Fig. 13. It is seen that the current traces do not exhibit the usual simple exponential decrement until about one second after the main breaker is closed. This effect occurred in all tests, but was less marked in tests 148 and 151.

The shapes of the current envelopes arise from the complex conditions existing during the tests. Thus, with a generator transformer, there are two coupled circuits and two time-constants, where the simple theory implies only one. Transformer magnetizing currents will affect the observed current envelopes, as also will the transient saliency of the rotor. In tests where the slip is sufficiently high (and 3% slip is equal to 10·8° per cycle), the change in machine impedance with angle will be important.

The initial currents largely magnetize the machine, and, as these fall, the currents which produce asynchronous torque first rise and then fall as the slip is reduced to zero. The values of rotor angle were recorded at one-cycle intervals. These results were tabulated, and the first and second differences, corresponding to slip and acceleration, were found. The accuracy of the method of measurement is stated[2] to be within ±0·5°. This accuracy, although relatively high in relation to present standards of rotor-angle measurement, is not sufficient to obtain the accelerations with reasonable consistency. The greatest second difference found (test 151) was −1·9°, i.e. an acceleration of −1·9° per cycle per cycle. This is equivalent to a per-unit accelerating torque of 2·45. Much larger transient torques can be obtained at the time of connection, but these could not be distinguished by the method of rotor-angle measurement used.

The approximate time for the slip to reduce to a negligible value, after the closing of the main breaker but before the closing of the field breaker, is given in Table 7. The relatively larger times required when running overspeed are probably due to the action of the governing system in admitting steam as the speed is reduced.

When synchronizing from speeds above synchronous, the turbine was run on the by-pass valve and the slip was restricted to less than 0·8% to minimize the danger of carry-over from the boiler. With this value of slip the machine, after synchronizing, carried a load of about 9 MW.

Table 7

Self-Synchronizing Tests

Test No.	Slip (+ = fast)	Maximum peak current as multiple of full-load peak current: Stator R	Stator Y	Stator B	132 kV breaker R	132 kV breaker Y	Maximum stator active power (+ = generating)	Maximum stator reactive power (leading)	Approximate time to reach zero slip
	%						MW	MVAr	sec
130	Very small	—	2·6	—	—	—	+2·0	85·0	0
148	+0·071	2·88	3·12	2·95	1·86	2·2	+15·9 − 3·2 +12·3	77·8	0
149	−1·64	3·22	3·32	2·78	2·93	2·56	−25·0 +10·0	71·2	1·0
150	−2·8	4·28	2·57	3·86	3·87	2·34	−33·0 +15·9	80·3	1·5
151	+0·241	3·4	3·58	2·45	4·26	2·75	−27·9 +12·3	73·4	0·8
152	+0·374	4·52	3·35	3·96	5·6	2·47	+14·7	82·2	1·2
160	+0·77	—	—	—	—	2·38	−15·1 +12·0	77·1	1·7
160A	+0·75	3·4	2·72	3·32	1·47	—	+20·7	87·3	—

(6.3) Self-Synchronizing as an Operational Procedure

It is useful to define the extreme values of slip at which self-synchronizing should be permitted. It is clear that the initial sub-transient currents (and therefore the peak value of current

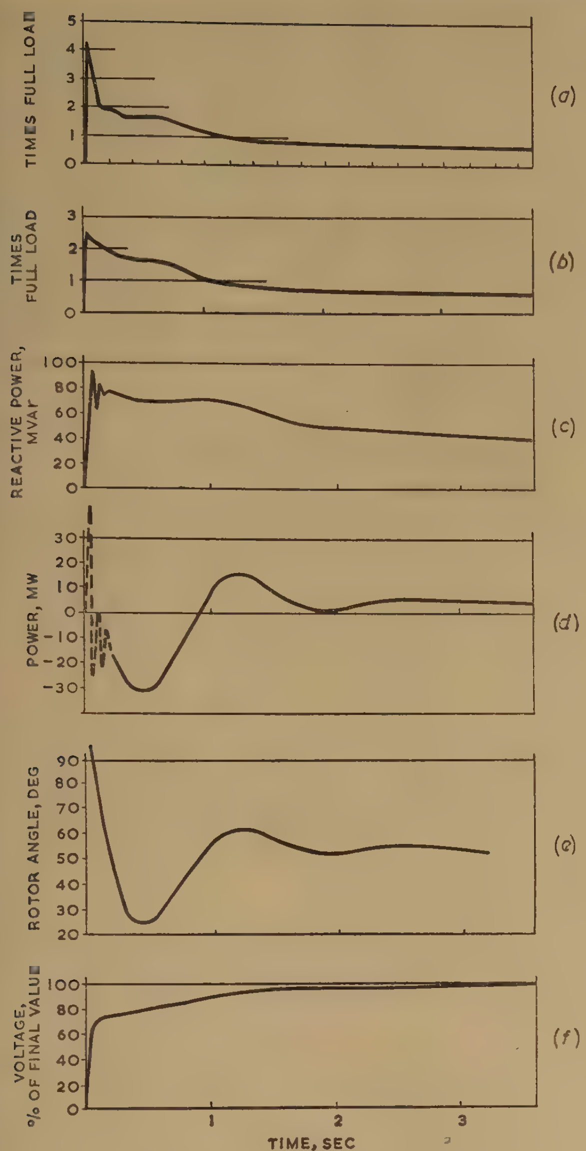

Fig. 13.—Synchronizing test No. 150.

(a) Stator current (red phase).
(b) Stator current (yellow phase).
(c) Reactive power.
(d) Active power.
(e) Rotor angle.
(f) Stator voltage.

and mechanical forces) will be little influenced by the value of slip. The asynchronous torque available reaches a maximum at a slip of about 0·5% (see Section 4.3.1), and will therefore never be large enough to damage the coupling on the prime mover.

One effect of increased slip is to lengthen the period during which the stator currents are large. A lower limit of 5% slip should meet all possible requirements without subjecting the stator to an unduly prolonged overload, but when operating above synchronous speed the action of the governor must be taken into account. If the generator could be successfully self-synchronized with a positive slip of 4% with a governor having a standard slope of 4%, the machine would pick up full load, and this sudden imposition might cause damage to the turbine. There might also be carry-over of water from the boiler, although this is unlikely to occur with the most modern designs. Self-synchronizing with positive slips of up to 5% should be attempted only if, as was done at Stella, the turbine is run on the by-pass valve; otherwise the positive slip should be restricted to 1%.

Apart from its emergency use, should self-synchronizing be adopted in place of the present synchronizing method? The most important objection to self-synchronizing is that the large inrush current at each connection, and consequential large mechanical forces in the end-windings, may eventually lead to damage to the insulation. This maximum mechanical force can be considered to be related to the peak current. The maximum peak current found at these tests and indicated in Table 7 was 5·6 times rated value. The calculated peak currents for 3-phase faults at the generator terminals and 132 kV busbars are 15·4 and 7·8 times rated value respectively, assuming maximum asymmetry and neglecting the decrement in the first half-cycle. If the peak currents for self-synchronizing are calculated on the same basis, assuming a short-circuit infeed of 2 500 MVA, a value of 6·8 is obtained. Since the mechanical forces are proportional to the squares of the currents, the forces at self-synchronizing would not be expected to exceed 75 and 20% of those for 3-phase faults at the 132 kV busbars and generator terminals respectively. There is therefore little likelihood of the self-synchronizing currents causing permanent deformation of the end-windings, but the small elastic deflections caused might eventually affect the insulation adversely. In this connection, Reference 8 reports 20 self-synchronizing connections during $1\frac{1}{2}$ years of a generator which had been in service 23 years and whose end-winding insulation is described as unsatisfactory. It is stated that no change in the condition of end-winding insulation was observed. It must be said, however, that a generator in this country on two-shift duty would be required to self-synchronize once and sometimes twice a day.

Voltage dips are unlikely to be troublesome. For example, with a comparatively low short-circuit level of 1 500 MVA, it is calculated that the initial voltage reduction on self-synchronizing a standard 60 MW set would be about 14%, and that this would disappear in less than one second.

(7) CONCLUSIONS

(7.1) Voltage-Regulator Performance

The tests carried out on the two different designs of high-response continuously-acting regulator show that they are capable of maintaining steady generator operation with rotor angles in excess of 90°. To give optimum results, the damping used is rather critical, and control with present designs is limited to rotor angles of about 135° with respect to the h.v. busbars. However, it is unlikely that in the foreseeable future the system will necessitate such equivalent leading reactive outputs at full-load, and, in any case, the stator current would appreciably exceed rated value under such conditions.

The continuously acting regulator and the reactive-power limiter tested at Stella North operated and maintained the reactive output very close to the limiter setting, and assuming that heating considerations permit, it should be possible to operate generators at leading power factors up to values corresponding to a rotor angle of at least 90° and still maintain a reasonable stability margin.

A recent paper[9] has drawn attention to the fact that the existing definition of nominal exciter-response is not applicable to exciters operating in conjunction with continuously acting regulators, and that there is no recognized definition for such excitation schemes. The results shown in Figs. 3 and 4 give a picture of the overall response at the terminals of a loaded generator for stator-voltage step changes. The initial maximum rates of change of reactive output for the normally inactive and continuously acting regulators were 10 and 20 MVAr/s

respectively, which, considering the relatively large time-constants in the complete loop, comprising regulator, exciter and generator, indicates a big response improvement with the continuously acting regulator.

The successful introduction of the continuously acting regulator has meant that, even though it may be necessary to operate at busbar power factors of 0·9 leading, values of short-circuit ratio (s.c.r.) can be appreciably lowered below the present general figure without exceeding safe rotor-angle operation. Fig. 14 shows how the machine s.c.r. varies with leading power

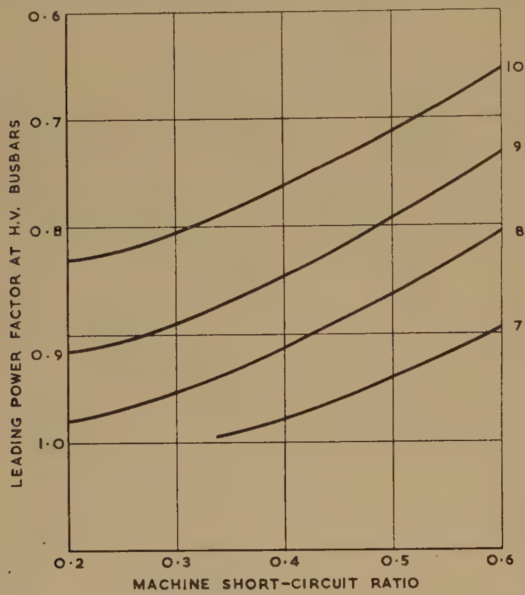

Fig. 14.—Relationship between short-circuit ratio and leading busbar power factor for rotor angles between 70° and 100°.

Assumptions.
(*a*) Generator rated power factor, 0·85 lagging.
(*b*) Generator terminal voltage maintained at nominal value by tap changing.
(*c*) Generator step-up transformer reactance, 17%.

factor at the high-voltage busbar for a particular rotor angle. Certain assumptions are made, and that of constant machine voltage by tap changing is only valid up to certain operating conditions. The number of transformer taps is limited, and, depending on the high voltage, which is regarded as being constant, the generator terminal voltage and output fall with increasing leading reactive output. This has to be considered when arriving at a machine s.c.r. for a particular leading power-factor limit. Until recently, large generators for connection to the 275 kV transmission system have, in general, been designed for a power factor of 0·85 and 0·6 s.c.r. On the basis of a maximum leading busbar power factor of 0·9, and limiting the rotor angle to 90°, the s.c.r. has now been lowered to 0·4. Such a reduction should effect savings in generator materials and, what is perhaps more important, the transport weight of the stator. Since generators are preferably built and tested in the manufacturers' works, the existing transport-weight restriction tends to limit the development of very large units. A saving, if only of the order of 8 or 10% on a 200-ton stator transport weight, could therefore be decisive.

(7.2) Stator-Core End Heating

The core end-heating tests, taken over a range of power factor, show an appreciable rise in temperature in the region of unity power factor, and indicate that the maximum rise would be at between 0·8 and 0·7 p.f. leading. At 0·9 p.f. leading, where future large generators may be required to operate at certain times, the temperatures of the machines tested were well within permissible limits. There are some differences between the Stella and Marchwood machines, even with rotor end-rings of the same material. The Marchwood figures are higher, primarily because the point at which the maximum temperatures were measured was not near a ventilated surface.

The very large machines now being built have stator ampere-turns per inch periphery loadings nearly twice those of the 60 MW machines tested. However, detailed modifications to improve the ventilation in the region of the stator-core clamp-plates, and the use of hydrogen pressures of 45 lb/in^2 (gauge) will ensure that acceptable limits are not exceeded. Heating tests on machines more highly rated than those tested are scheduled for the near future.

(7.3) Asynchronous and Out-of-Step Operation

The tests have shown that, with increasing values of slip, there is a rapid increase in generated power up to a maximum, but the peak value depends on the value of the stator voltage and the rotor-field connections. For the 60 MW machine tested, the peak occurred between about 0·5 and 1·5% slip, and at higher slips there was a reduction of power. If, when operating at full load, the excitation were lost, the machine would run asynchronously at a slightly lower load but with a stator current much higher than rated value. If the steam input to the turbine were not quickly reduced, the overcurrent protection might, depending on its setting, trip the set. However, if load is reduced quickly to about 50% rated value, the stator current will be about normal, and the operator can take steps to restore excitation. Such operation should be possible for prolonged periods unless it gives rise to unacceptable voltage reduction on the supply system.

To the operator in a power-station control room, the only evidence of asynchronous or out-of-step operation of a machine is that the control-panel instruments are either off scale or oscillating violently. In most cases it will be possible to distinguish which of the generators is operating abnormally, but if rotor-angle indicators are provided this will be clear in all cases. The appearance is one of crisis, but these tests have shown that in most circumstances the generator can be operated at reduced load and need not be disconnected from the system. The simple rule appears to be to reduce the steam supply to the set until the stator current is reduced to the rated value. This should cover all cases except those in which there is a widespread breakdown of synchronism throughout the system.

Where automatic regulators with reactive-power limiters are used, the possibility of slipping poles due to excessive reduction of excitation is remote. For normal fault-clearance times, instability due to external faults also rarely occurs. Where the clearance times are excessive and synchronism is lost the machine generally resynchronizes. The position may not be quite so favourable where the rating of the machine concerned is relatively high with respect to the rest of the system. Where this condition arises, a more closely integrated system of turbine and generator control, sensitive to load, voltage, reactive power, rotor angle, slip and speed, may be desirable.

(7.4) Self-Synchronizing

The tests established that self-synchronizing is a practical operating procedure for generators provided with step-up transformers. There was some minor trouble with the field-breaker auxiliary contacts, due to incorrect time sequence, but voltage dips with a local short-circuit level of about 2 500 MVA were small, and there were no adverse thermal or physical effects on

the generator, as far as is known. Self-synchronizing can therefore be used in an emergency to connect a generator to the system, and the procedure used in the tests could be adopted. It would be most convenient to connect when the slip was negative rather than positive, and the field breaker may be closed at any time after the transient inrush currents have become small, say 0·5 sec after closing the main breaker. It would be prudent to allow a larger interval of time to avoid the possibility of switching in the field before the main breaker is closed, and 5 sec might be appropriate. The provision of remote electrical closing of the field breaker would be useful.

The use of self-synchronizing as a normal operation feature appears attractive where completely automatic control is required, or where the distance of a circuit-breaker from the generator it controls makes the synchronizing equipment elaborate and expensive. However, the end-winding insulation might eventually suffer some damage, and self-synchronizing has not so far been considered justified for turbo-generators in this country. Further tests on a machine which is frequently synchronized are being considered. The number of connections to the system could be recorded, and the stator winding pressure-tested at intervals when the end-connections could be inspected. The introduction of gauges to measure deflections at various points in the end-windings would b an advantage.

(8) ACKNOWLEDGMENTS

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DISCUSSION BEFORE THE INSTITUTION, 5TH FEBRUARY, AND THE NORTH-EASTERN CENTRE, AT NEWCASTLE UPON TYNE, 26TH JANUARY, 1959

Mr. W. D. Horsley: The authors' tests show the efficacy of automatic voltage regulation in maintaining the stability of an alternator operating with rotor angles well beyond the theoretical limit. In 1935 I suggested* that, even with a low short-circuit ratio, a moderate excitation response would be adequate. If further tests are planned, it would be valuable to establish the minimum rate of excitation response required.

In stator-core end-heating the authors find that the hottest positions are near the bottom of the slots. This would be expected from theory, except possibly in an alternator with very wide teeth. It would also be expected that the hottest position would be at the extreme ends of the core and that the heating would penetrate only a short distance axially into the laminations. As shown in Fig. 5, the thermocouple indicating the maximum temperature rise is placed on the second core section. The couple in a corresponding position on the first section, in which the loss might be expected to be greater, gave a lower reading. There are probably several reasons for this: the section has a larger air-gap and carries a relatively smaller proportion of the main flux; it is in contact with the core end-supports (which has a low temperature rise in this machine) and the section is narrow and cooled on both sides.

It is stated in Section 3.6.3 that the temperature rise at a hydrogen pressure of 4 lb/in^2 varies as (stator current)$^{1\cdot 2}$. This figure must depend upon a number of factors, one of which is the relative level of the general background heating, but the results seem to confirm the theory of end-leakage flux heating outlined by Richardson,* who showed that this flux may be regarded as the vector sum of the leakage fluxes due to the rotor and stator windings. If the end-heating is considered in terms of m.m.f. rating at constant short-circuit ratio, it may be expected to vary more nearly as the square of the specific loading, and the advantage of the non-magnetic end-caps becomes more apparent.

The authors' reasoning to account for the difference between curves (*a*) and (*b*) in Fig. 7 is difficult to follow and a more detailed explanation would be helpful.

The test data given in Section 4 are valuable, particularly in indicating the shape of the slip/load characteristic. Some of the conditions of operating appear severe, but the rotor was carefully examined on both the occasions when the caps were changed and no signs of damage were detected.

The results of comparative tests carried out with magnetic and non-magnetic end-bells are of particular interest in view of the use of both types by various manufacturers. On the Stella

* HORSLEY, W. D.: 'The Stability Characteristics of Alternators and of Large Interconnected Systems', *Journal I.E.E.*, 1935, 77, p. 577.

* RICHARDSON, P.: 'Design and Application of Large Solid-Rotor Asynchronous Generators', *Proceedings I.E.E.*, Paper No. 2492 S, January, 1958, (104 A, p. 332).

machine the excitation required for normal voltage on open-circuit increased by about 7% with magnetic end-bells fitted and the excitation required for rated load increased by just over 5%.

It is stated in Section 4.3.3 that increased iron saturation will produce a greater skin effect. Would not increased saturation reduce the permeability of the iron and therefore produce less skin effect and a smaller equivalent rotor resistance?

The differences in frequencies in Table 5 are attributed to the effect of the voltage regulator. Are they not primarily due to the difference in the strength of the generator field with the change in transformer tappings?

Mr. L. W. James: In recent papers before The Institution there have been a number of references to the value of rotor-angle indicators on the generator control panel. Although in Section 3.1 the authors say that these are not generally provided, in Section 7.3 they state that, in the event of an out-of-step operation, the provision of rotor-angle indicators will show clearly which of the generators is operating abnormally. Since, on an average, there are some 200 instruments for a unit operator to look at, any addition to this number must be considered very carefully to see whether it is really essential. With the use of modern regulators with stability relays as suggested in the paper, the possibility of out-of-step operation is more remote than in recent years, and rotor ammeter readings would appear to indicate this kind of operation equally well if the readings were compared with those for similar sets in the same station.

Fig. 4 shows the rotor current for unstable operation. What effect has unstable operation of one set on the rotor current of other machines in the station? One would imagine the oscillations would be much smaller and would be about a higher mean value. It should be quite simple to decide which of the sets is operating incorrectly.

In Table 2 the rotor-angle for hand and normally-inactive-regulator control varies from 92° and 97° to 72° and 79° and back again to 78° and 95°, which is not very consistent. Can the authors give any explanation?

Dr. F. Busemann: In Section 5.3.3 the authors say that the governing system had no positive effect in achieving resynchronization. Is this fair to the governor, because it is in direct contradiction to what was found at Cliff Quay? Fig. 11 suggests that the governor had shut down to some extent and gave just the right encouragement to resynchronization at the cycle when the machine resynchronized, while the other quantities did not show any particular change. For comparison, Fig. 4 of Reference 10 shows one example from the Cliff Quay tests where the steam power was recorded. When the machine slipped two pole-pairs forward, the steam input was entirely shut down; when it slipped one pole-pair backwards, the governor valves re-opened immediately. I assume that this governor responded more strongly than that of Stella and that we did not have so many poles slipping.

The damping torque coefficients given in Table 5 are in good agreement with those found at Cliff Quay. In particular, the fourth case comes nearest to the conditions at Cliff Quay, where there was also some impedance between the test generator and the system.

Mr. V. J. Vickers: From Figs 5 and 6 it appears that the Marchwood machine has a core-end temperature rise about twice that of the Stella alternator. I believe that significantly higher temperatures would have been measured if the Stella thermocouples had been embedded in the centre of the end-packet of laminations instead of in the first vent duct, not only because of the elimination of the indeterminate cooling of the couples and their leads (however well-screened) when placed in the ventilation ducts, but also—and more particularly—because of the very much more localized heating at the extreme end. This latter point is emphasized by comparing the temperatures at points A and B at Marchwood. Point B is in the centre of the second packet and is only 2 in axially displaced from A, yet the temperature rise there at 3 kA and 0·8 power factor loading is reduced to as little as 21° C compared with 64° C at A.

Further thermocouples, not shown in Fig, 6. were built into the Marchwood stator at points corresponding to A, but positioned radially half-way between the back of the slot and the back of the core. The temperature rise recorded under the same loading was 19° C lower than at point A. As has been pointed out, the effect of hydrogen pressure is very appreciable, and it should be noted that the Marchwood machines were designed for operation at 15 lb/in^2 but, having considerable temperature margins in hand, are normally operated at about 4 lb/in^2.

Fig. 8 shows that only under favourable conditions of transformer tap position can resynchronization following loss of field be expected, unless some deliberate reduction in steam input is made. This means that, with the more highly rated machines now being built, quite a substantial reduction in load must be made to ensure pulling in after field restoration. If it is appreciated that a quick reduction of load and restoration of the field will achieve resynchronization, there should be no cause for panic when oscillation of meters is observed. I agree that asynchronous running should be demonstrated to control room staffs with the object of familiarizing them with the symptoms and the corrective measures necessary.

Mr. K. J. H. Thomson: The use of direct water-cooled stator windings has removed present limitations to stator-winding loading, and turbo-generator output for given shipping dimensions is primarily limited by rotor heating. Hence a reduction in short-circuit ratio from 0·6 to 0·4 in a highly rated generator of 300 MW at 0·85 power factor can reduce the weight of the stator heaviest lift by 9%. Alternatively, for the same size of machine, an increase in efficiency of about 0·15% results.

Recent tests have shown that the continuously acting regulator can ensure dynamic stability of machines up to load angles of over 130°.

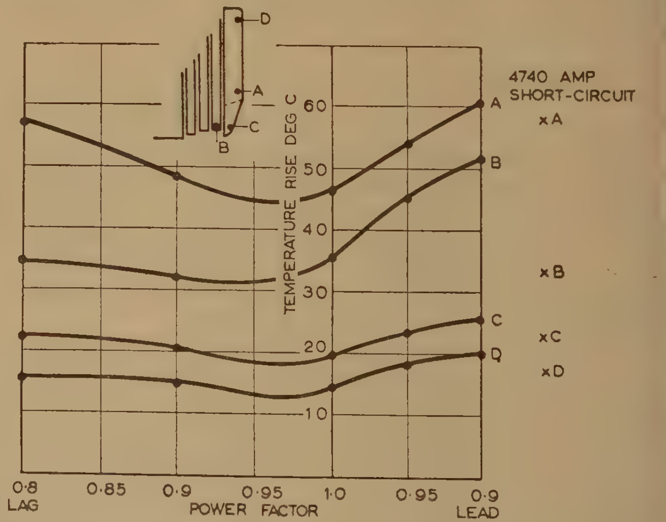

Fig. A.—End-iron temperatures on 100 MW 13·8 kV turbo-generator at 102 MW

½ lb/in^2 hydrogen pressure.

Fig. A shows end-iron temperature rises at four points taken at constant load and varying power factor on a 100 MW 13·8 kV generator. These machines were designed for operation at ½ lb/in^2 hydrogen pressure and are faily highly rated for machines at this pressure. They have non-magnetic rotor-coil retaining

rings and stator end-plates. Various short-circuit tests were made on the same machine and some temperature rises are shown. No simple direct relationship between stator current and end-iron temperature rise was found, since the temperature is also affected by the rotor m.m.f. and by normal iron heating.

Recent tests on a 120 MW machine at 30 lb/in^2 hydrogen pressure have demonstrated that end-plate temperatures on short-circuit are no higher than those on the 100 MW machines at $\frac{1}{2}$ lb/in^2 despite an increase of more than 30% in stator m.m.f. Comparative tests on machines of similar construction have shown that end-plate temperature rises are from 45 to 60% lower at 30 lb/in^2 than at $\frac{1}{2}$ lb/in^2.

These tests indicate that, with proper attention to ventilation design, end-iron heating should impose no design limitation up to the largest ratings at present envisaged.

Mr. W. Casson: Reference is made in the paper to the first of the series of tests carried out at Little Barford in 1951, the results of which were unfortunately not published. The limit to asynchronous operation was determined by means of temperature-indicating paints applied to appropriate parts on the stator and rotor. A 30 MW machine was operated asynchronously at nearly half load for four hours. From these tests we have learnt that, with suitable voltage regulators, generators can be operated on leading power factor with reduced stability margins; but I think the stability margin should not be reduced to such an extent that the generator would become unstable should the voltage regulator stop functioning. In designing future generators, to take account of the increased range of power factor which can be allowed by fitting continuously operating voltage regulators, will the transient stability be impaired? Also, in practice, is it wise to reduce the range of excitation in order to reduce the size, and therefore the cost, of the machine, bearing in mind that, while such a range will be suitable for the base-load conditions which will apply for a few years, it may not be suitable for the conditions which will apply when not running on base load in later years? I cannot see any great need for operating synchronous generators asynchronously, unless there is scope, under high-voltage conditions, for operating say one generator asynchronously at reduced load to consume reactive power in preference to operating all the generators at leading power factor. Would the amount of reactive power consumed by this method of operation be greater than in the alternative method, and would the remaining machines be more stable?

Self-synchronization seems at first sight to be very attractive, particularly as an emergency measure, but when investigated it is found that the disadvantages outweigh the advantages, and it does not seem likely to become a regular operation.

Mr. V. Easton: When considering the dynamic stability of an alternator and its associated excitation circuit there are two points which must be kept in mind. First, the optimum damping incorporated in the regulator varies with the loading condition. To adjust to the somewhat critical value required to obtain the greatest stable angle will adversely affect operation at no load and at normal angles, which is the more important condition. Secondly, the alternators described in the paper are relatively lightly rated in comparison with present trends, particularly with direct rotor cooling, so that the results of the tests may not be directly applicable to future designs. This is because three factors primarily affected by the use of direct rotor cooling—the inertia constant, the circuit damping and the field time-constant—also play an important part in determining the best stabilizing effect at these high load angles. The point which becomes very apparent is the advantage in designing the alternator, the excitation circuit and the voltage regulator as an integrated unit.

The fundamental criterion of stability is one of load angle and not reactive power, and it is the better choice to provide a signal to the voltage regulator. Even at loads below the static stability limit it makes available, with safety, increased capability at leading power factors. A limiting angle as low as 65° applied to Fig. 1 would be a straight line passing through the points (45 MVAr, 0 MW) and (18 MVAr, 60 MW), and the increased capability is clear. An angle of 65° is very conservative, since general experience has shown that 90° can be readily maintained by hand even with a slow-response shunt-wound exciter. In this respect curve (*a*) appears unnaturally low and of little practical value.

Mr. J. G. Miles: The satisfactory agreement obtained between the calculated and test results for the performance of the continuously acting regulator is important as an aid in designing the optimum regulator for any particular installation, and to enable the effects of regulators of this type in other applications to be predicted.

Among these a case of particular interest is that arising when the external impedance between the machine and an infinite busbar becomes large (i.e. comparable with the synchronous reactance of the machine). This condition may be encountered when supplying large loads from remote stations to a metropolitan area. Fig B shows an idealized case based on an actual

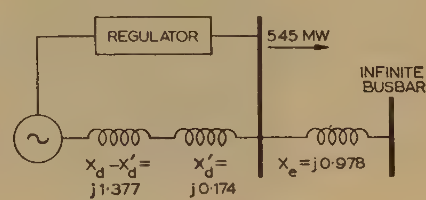

Fig. B.—Dynamic stability with high external impedance.
Reactances per unit on 600 MVA base.

network. This consists of a 600 MW station supplying power at 220 kV to a remote load area, line-construction requirements at times making single-circuit transmission essential. In this case the machine will be operating at a lagging power factor with near-normal excitation, and the main function of the regulator will be to enable powers near the static stability limit of the line to be transmitted with acceptable terminal voltages and reactive output at the sending end. This is illustrated in Fig. C, which

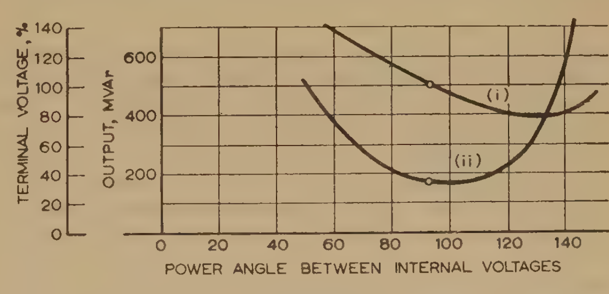

Fig. C.—Variation of (i) machine terminal voltage and (ii) reactive power for constant output and receiving end-voltage.
○ Proposed operating point.

shows the sending-end voltage and reactive output as a function of rotor angle for constant power output and receiving-end voltage. Operation at a power angle of 93° gives sending-end values within the machine rating. The theoretical stability limit at this power is 115°, but this margin cannot be fully utilized since, because of the high line impedance, further reduc-

tion of terminal voltage causes an increase in reactive power output and not a continued decrease. On systems with high external impedance this factor may set a subsidiary limit to the maximum operating angle which is independent of machine or regulator characteristics.

Mr. K. C. Parton: My experience has been with a continuously acting regulator on a 60 MW direct rotor-cooled alternator at Poole power station. A small permanent-magnet alternator incorporated with the shaft-driven turbine supervisory gear is included to provide a rotor-angle signal which is employed in two ways. First, it operates an angle indicator installed in the control room, where it provides a continuous and accurate indication of the stability margin under both steady-state and transient conditions. From past experience, operators prefer the meter to stability-limit charts. Secondly, the signal is used to prevent the machine advancing beyond a preselected angle by automatically introducing rotor-angle control. The transient disturbance shown in Fig. D is normally sufficient to cause loss of synchronism. The set can be seen to be falling out of step until restrained by the angle limiter. The performance during a test when suddenly reducing the automatic-voltage-regulator setting was similar, except that damping was much better. For both tests the limiter was set near 110°.

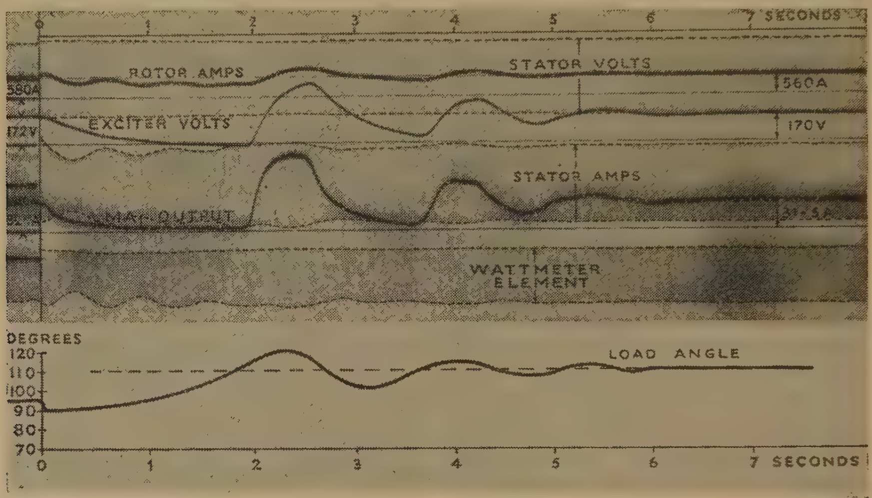

Fig. D.—Rotor-angle limiter preventing instability after line-switching disturbance.

	Initial reading	*Final reading*
Power, MW	58·72	58·8
Reactive power, MVAr	31·4 (leading)	57·6 (leading)
Stator voltage, kV	11·45	11·88
Stator current, amp	3 330	3 960
Load angle, deg	95·5	109·5

MA, output = Main exciter field current.

A further application is the possibility of using an angle-derivative signal for normal regulator damping. Simulator studies show that this can add at least a further 20° to the steady-state limit, and tests will be made to prove this point in practice. In general, a rotor-angle signal which is accurate during both steady-state and transient conditions can be of much assistance in alternator control.

Mr. E. B. Powell: The action of the voltage regulator when the reactance of the system is changed by switching, shown in Table 4, is of interest. Similar tests were carried out in London in 1955 which showed that a Tirrill regulator would bring the machine back immediately into the stable quadrant.

During a special course of lectures on machine stability given in London, the staff observed the behaviour of the switchboard instruments on a 20 MVA machine carrying half load when it was made unstable. They observed the movement of the rotor by stroboscopic means. It was also demonstrated that the Tirrill regulator was sufficiently quick acting to maintain a steady input with a rotor angle of 115°. Old machines equipped with these regulators can no doubt be used to better advantage if this fact is fully appreciated.

In all future tests a thorough investigation into the behaviour of the turbine governor and boiler controls should be included. We have a reasonable knowledge of how the generator will operate under both unstable and asynchronous conditions, but we do not know what happens on the water and steam side of the system, and this is probably of greater importance than the electrical end. The operating staff are much more alarmed at the heavy valve pumping, which is almost invariably set up and causes heavy vibration of the steam ranges, than at the behaviour of the generator. If the operators also expect the boiler controllers on a unit system to get out of step under asynchronous running and to shut down the boiler completely, as at Stella, they will be very loth to operate the plant anywhere near the stability limit. If the behaviour of all the equipment is known, means can no doubt be found for preventing this rather alarming repercussion.

Mr. J. A. Soper: The Tirrill regulator referred to by Mr. Powell restored the generator to a stable rotor angle after a swing to 150°. As the exciter was a simple shunt machine, the performance of this old regulator was remarkable. In the paper, a change of 50 MVAr beyond that necessary to balance the limiter is shown in Fig. 3. This is a large increase, as the authors point out. If generators are running close to limiter operation, an increase in excitation of this order will cause cascade operation of all regulators fitted with these relays and possible instability of generators controlled by regulators not so fitted.

From Fig. 1 it will be noted that, on hand control, the reactive range of this generator is 80 MVAr. This causes an approximate change of 15% in the generator terminal voltage and this range could be extended by system voltage variations. Interpretation of the power chart for abnormal voltage conditions becomes difficult, and an error of 10–15° in the rotor angle could occur

and lead to a dangerous condition. For this reason I agree that a rotor-angle indicator is desirable, because one rotor-angle/power-line would ensure a true stability margin under all conditions. Present trends towards lower short-circuit ratio, machine inertia and stability margin, together with greater generator-transformer reactances, increase the need for rotor-angle indicators. The last column of Table 3 gives a 9% stator-voltage change, while the continuously acting regulator has a sensitivity of about 0·2%. Is this 2% increase due to the effect of high-angle running on the regulator voltage-sensing elements?

Mr. D. R. Fenwick: The value of the tests to designers of automatic regulators cannot be over-estimated. The success of the magnetic-amplifier regulator with amplidyne has been established, and future development of this and other types can now be built on facts rather than theory. A particularly encouraging aspect of the tests lies in the close agreement between the results obtained and those predicted by the analogue computer.

Fig. 3 demonstrates the operation of the reactive-power limiter associated with the normally inactive regulator, the action being rather coarse. At the set limit the power-measuring relay closes contacts to adjust the motor-operated voltage-regulator setting rheostat in the 'raise excitation' sense. Subsequent to the tests, greatly improved results were obtained by reducing the speed of traverse of the setting rheostat.

The reactive-power limiter associated with the continuously acting regulator comprises a static network which is energized from the voltage and current transformers normally associated with the automatic voltage regulator. At the pre-set limit a recalibrating signal is circulated through an auxiliary control winding of the regulator.

In Section 7.1 the authors have drawn attention to the critical nature of the damping in achieving optimum results, and it is a matter for regret that sacrifice of open-circuit performance is frequently necessary to obtain the best results in the dynamic zone. It is possible to overcome this difficulty, and feedbacks derived from speed, power or pole angle are often helpful. In the case considered such artifices were not employed, and the same feedback settings were used for both dynamic-zone and open-circuit tests. It was confirmed that the time-constant of the feedback derived from the main exciter armature was most significant and that this must not be less than that of the main exciter if satisfactory results are to be obtained.

While the Tirrill regulator is truly continuously acting and has the required dynamic characteristics, it is very limited in its power-handling capacity and therefore belongs very much to the past.

Mr. B. Barker (*communicated*): The authors have shown that during asynchronous running the stator current fluctuates at twice the slip frequency owing to the geometry of the rotor, giving rise to differences in pole impedances for the direct and quadrature axes. For a given load the slip is lowest when the rotor field is short-circuited; however, under this condition the percentage fluctuation in stator current is greatest.

The tests carried out at Little Barford in 1951 showed that the fluctuation in stator current increased with load, and at 50% normal power output was ±24% with the rotor windings short-circuited and ±7% with them open-circuited. These are more than those obtained at Stella North, where values of ±5–15% with the field discharge resistance connected and ±2 to 3% when open-circuited were obtained. This difference may be largely due to the materials of the rotor slot-wedges, since the Little Barford machine has a higher proportion of non-magnetic wedges.

Should not the percentage fluctuation in stator current, its maximum amplitude and perhaps its frequency be taken into account, together with the curves shown in Fig. 10, in assessing its capabilities of asynchronous running?

With the much higher electrical loadings now being used on modern generators, which will still further be increased if the short-circuit ratio can be reduced below the levels currently in use, the maximum percentage power output obtainable under asynchronous running conditions will be appreciably reduced, as will the output at which it will be possible to re-synchronize. What action will be necessary by operating staff if excitation is lost on such highly rated machines?

Prof. J. C. Prescott (*at Newcastle upon Tyne*): In preserving the stability of a machine which is to operate at load angles greater than 90°, the automatic regulator is called upon to counter the fall of electrical power which occurs with increasing angular displacement by increasing the generated e.m.f. of the machine. The effectiveness of this form of stabilization must clearly depend upon the rate at which the increase in e.m.f. can be achieved in relation to the rate of growth of the load angle, and I should like some figures on this. In Table 3 the time of operation seems to range from 1·8 to 29 sec.

When asynchronous running is contemplated one must ask whether the oscillating torques which accompany pole-slipping are acceptable to the machine designers. If they are, their effect upon the machine itself may be unimportant; but it would seem that the large synchronizing currents which are brought into play may cause periodic disturbances throughout the network, to which other machines connected to it may respond. In Fig. 11 the output power of the machine shows a periodic disturbance of about 1¼ sec, which might be felt acutely by any other machine connected to the network and having a periodic time near this value.

With regard to the self-synchronizing tests, what are the alternative values under 'maximum stator active power' given for tests 148–151 in Table 7?

Mr. C. C. Baxendale (*at Newcastle upon Tyne*): Section 3.4 discusses the over-correction of the limiter on the normally inactive regulator (see Fig. 3): this point was suspect before the test and has now been satisfactorily corrected.

The chart records for test 167 (Fig. 11) show that the automatic voltage regulator responded well to the changes impressed on it. Would it be preferable, under conditions of pole-slipping, to obtain a continuous 'boost' signal from the regulator and thereby achieve earlier synchronizing? The 'boost' could be obtained (as a secondary condition) from the limiter unit.

Further calculations have now been made in connection with the behaviour of the 132 kV over-current relay under pole-slipping, asynchronous running and external fault conditions. Fig. E shows the calculated h.v. current/time curves for (*a*) 132 kV phase-to-earth condition with and without the automatic voltage regulator, (*b*) an external 132 kV 3-phase fault with and without the regulator, (*c*) pole-slipping at full load with a high-impedance tie to the system (test 51A), and (*d*) asynchronous running at full load and a slip of 2·85% (test 135B). With its normal settings of 525 amp and 0·66 time multiplier, the relay was found by test to have the following operating times:

Table A

Condition	Automatic voltage regulator	Operating time	Estimated rotor time rating
		sec	sec
132 kV phase-earth fault ..	In	4·5	6
132 kV phase-earth fault ..	Out	5·1	10
132 kV phase 3-fault	In	20	>30
132 kV phase 3-fault	Out	No operation	>60
Pole-slipping (test 51A) ..	—	28	30
Asynchronous running (test 135B)	—	22	>30

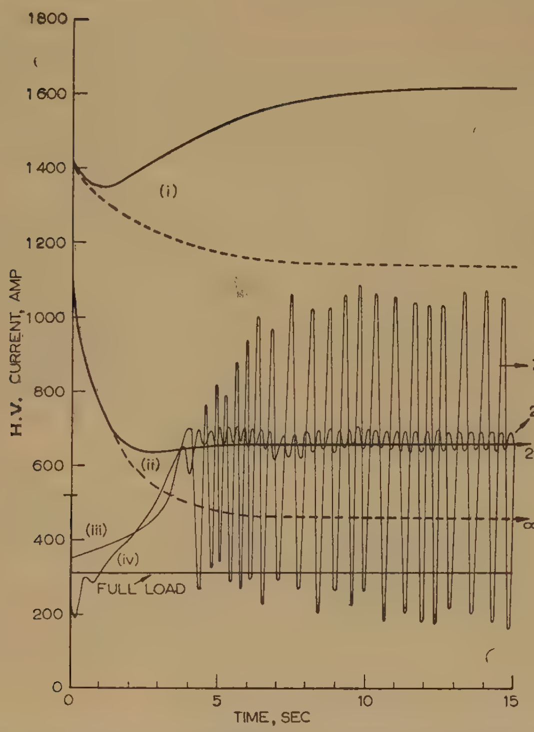

Fig. E.—Pole-slipping and asynchronous running curves and calculated fault values with and without automatic voltage regulation.

(i) Phase-to-earth fault.
(ii) 3-phase fault.
———— With automatic voltage regulation.
— — — — Without automatic voltage regulation.
(iii) Pole-slipping test 51A.
(iv) Asynchronous running test 135B.

With these settings the relay gives a fair measure of protection under abnormal symmetrical conditions as well as full protection against sustained 132kV earth faults. Should a fault between two phases occur on the stator, the relay will operate after about 4sec in the event of failure of the instantaneous Merz–Price protection.

Mr. R. A. Hore (*at Newcastle upon Tyne*): The explanation of dynamic stability seems to be substantially that of Dahl.* Another explanation, more useful in forming the basis of a usable theory of performance, is as follows:

The effect of a 'perfect' regulator would be to maintain the initial field-winding transient (and hence the air-gap flux), thus equivalent to reducing the effective direct-axis reactance, X, of a machine from the synchronous to the transient value. Although no regulator achieves this, under 'steady-state' operation an equivalent X may be calculated, behind which a continuously acting regulator may be assumed to maintain a constant equivalent voltage. A salient-pole machine normally has $X = X_d > X_q$, and its power-angle curve, given by

$$P = \frac{EV_t}{X_d}\sin\delta + \frac{V_t^2(X_d - X_q)}{2X_dX_q}\sin 2\delta$$

has a second-harmonic component which is positive between 0 and 90°. The voltage regulator renders the effective X less than X_q, and the second-harmonic term of the power-angle curve is thus negative, so that at low excitation the peak of the power-angle curve lies near 135°. This explains operation at load angles above 90° and also permits the construction of performance charts on familiar lines. The chart for the Stella generators is shown in Fig. F.

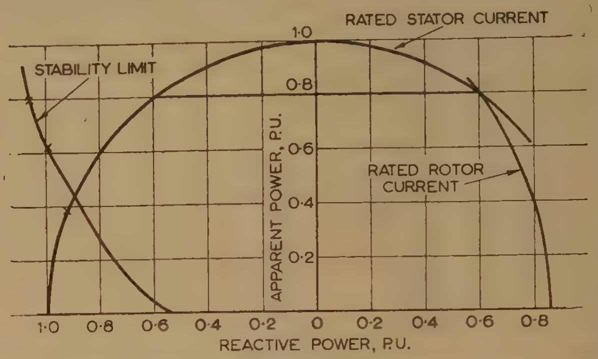

Fig. F.—Performance chart for Stella generator.
× Test results

The regulator has little effect on the theoretical capacity of the machine at zero power factor although it increases its stability, but at any load above the minimum turbine load its effect is to remove stability considerations, and core-end heating becomes the operating limit at leading power factors.

This chart and the results in the paper apply to a single machine operating on an 'infinite busbar', but, in practice, a whole station will usually run with a leading power factor. These charts can be used perfectly satisfactorily by taking account of external reactance only to the extent that it produces a lowered terminal voltage, and the appropriate chart must be used. As a result the usable leading capability of machines is not as great as the paper might be thought to imply.

Section 4.3.1.—The approximate peak of the torque/slip curve can, in fact, be found theoretically, and such estimates have been found reasonably accurate.

Sections 4.4.1 *and* 7.4.—I agree with the authors' comments on the shortcomings of field circuit-breakers, and the need for power closing. For coarse synchronizing the discharge contacts should be designed for the appropriate 'break' duty as well as the 'make' operation.

Section 6.3.—The authors accept a voltage drop of 14%. Where does this occur? Also one should remember that coarse synchronizing may be undesirable on a system operating under emergency conditions.

Section 7.3.—It is less likely that a single machine will lose synchronism than a whole station, so that the multiple pole-slipping may involve a large equivalent machine. While one might agree that damping may be such that pole-slipping is not as serious an occurrence as was thought, it will almost certainly result in the general break-up of the load, and so lead to a widespread failure.

Section 5.3.4.—Subsequent tests, during which the machine resynchronized, have generally confirmed the behaviour of the voltage regulator during out-of-step operation. I agree that at high slips the result might well be less fortunate, and in any case is likely to disintegrate the load.

AUTHORS' REPLY TO THE ABOVE DISCUSSIONS

Mr. T. H. Mason, Dr. P. D. Aylett and **Mr. F. H. Birch** (*in reply*): The replies have for convenience been grouped under broad subject headings.

Stability and Voltage Regulators.—In reply to Messrs. James and Easton, one of the difficulties in taking steady-state stability tests, especially under hand control of excitation, is knowing how near one may approach the limit without seriously risking

* DAHL, O. G. C.: 'Electrical Power Circuits' (McGraw-Hill, 1938) Vol. II.

instability. The grading of the exciter rheostat, the steadiness of the load, the turbine-governor response and the risk the operator is prepared to take of slipping poles, all influence how near the limit is approached. There is, in any case, difficulty in defining this limit since on reaching it there is a slight drift and eventually a rapid acceleration, and the point of transition between stable and unstable conditions is not clear. The human element is the main factor which explains the slight inconsistency in the test-limit readings under hand control of excitation shown in Fig. 1. Under steady load conditions manual excitation control at rotor angles of 90° to the high-voltage busbars have, to the authors' knowledge, been obtained on one occasion, but such instances are exceptional. The limit curve (*a*) of Fig. 1 does not differ appreciably from the general case, bearing in mind that the transformer impedance drop is not included.

Several speakers have drawn attention to the use of rotor-angle indicators. We agree with Mr. James that there is little point in providing unit operators with rotor-angle indicators. The references to such instruments in Sections 3.1 and 7.3 were intended to apply to electrical control rooms where comparatively few instruments are installed. Where loss of field or pole-slipping might pass unnoticed in an electrical control room remote from the steam plant, it would be better to provide an alarm operated by stator current in excess of, say, 110% rating or by rotor slip, to enable the operator to unload immediately the generator concerned. Such action, if taken promptly, would prevent the overcurrent protection shutting down the machine, would prevent overheating of the stator and rotor and would facilitate resynchronizing in the case of pole slipping. In stations where the electrical control is carried out by the unit operator, the alarm mentioned would be less effective as its operation would be accompanied by other turbine and boiler alarms. Instead, it might be worth while arranging for the device, initiated by stator current or rotor slip, to unload the machine automatically.

Mr. Casson questions whether operating at rotor angles as high as 90° is permissible, since the automatic voltage regulator may stop functioning. Experience with continuously acting regulators has so far been very good, but if failures should occur, the manual excitation, which has automatic 'follow up', takes over control. In practice, the leading-power-factor requirements are expected to be such that even with 0·4 s.c.r. machines, a setting of about 80° will be satisfactory. In the event of regulator failure and automatic transfer to hand control, the operator is given an alarm signal to enable him to increase the excitation, if necessary, to ensure stable operation. If the system leading-power-factor requirements become such that operation at rotor angles as high as 90° is required, a minimum setting of hand rheostat could be chosen to ensure stable operation in the event of automatic changeover.

It is unlikely that the reduction in short-circuit ratio will in itself have any effect on the transient stability limit, since this depends largely upon the transient reactance of the machine. Large highly rated machines tend to have higher reactance, and consideration is being given to trying to limit this characteristic. If a generator, taking advantage of a high-speed regulator, is operated at large rotor angles, it is possible that the transient stability margins will be smaller so that shorter fault clearing times will be required. It is not proposed to increase the rated lagging power factor of large machines above the present figure of 0·85.

The authors agree with Mr. Easton that the best turbo-generator performance will be obtained when voltage-regulator design is co-ordinated with machine design. The Poole test result given by Mr. Parton compares closely with the result shown in Fig. 4 of the paper. The excitation limiter initiated by rotor angle has been shown to be completely satisfactory and clearly has other potential uses.

The system shown by Mr. Miles is very interesting although such conditions are unlikely to arise in this country. A comparable case of which we have had experience is a generating station supplying a low-power-factor load in excess of its active power capacity, the remaining active power being imported over a system of comparatively high reactance. In this case, instability occurred when the machines in the generating station were fully loaded and operating at rated lagging power factors.

The reference by Messrs. Powell and Soper to the ability of the Tirrill regulator to control generators with rotor angles exceeding 90° is timely, since this fact may not be generally appreciated. As indicated by Mr. Fenwick, this regulator's capacity may not be suitable for modern large units, but where it is installed operation engineers will, no doubt, wish to determine what leading reactive outputs are possible.

The difference of 2% referred to by Mr. Soper is due to the method of calibrating the nominal step changes. These were established by finding what change in resistance in the regulator reference circuit was required to give the desired step change in machine open-circuit voltage. The same change in resistance naturally produced a different voltage change on load.

Professor Prescott asks for further information with regard to the stability of the machine at load angles greater than 90°. The description given in Section 3.2 is the best simple explanation we can offer. The complex operation of the regulator and excitation can be described in detail only in terms of high-order differential equations solved by the method given in Reference 1.

Mr. Hore's explanation for high-speed regulator performance in terms of an equivalent direct-axis reactance may be of some assistance in power-system design work. However, he does not disclose his method of computing the value of the equivalent reactance to be used. The approximate peak of the torque/slip curve can be found if an equivalent circuit can be derived for the machine, but it is difficult to do this for a turbo-generator where the current paths in the solid rotor are largely affected by iron saturation and skin effects. The derivation of equivalent circuits for salient pole machines is very much simpler.

Stator-Core End Heating.—The authors thank Mr. Horsley for his comments, particularly those on end-iron heating. Without a detailed knowledge of the American machines referred to in Fig. 7, the explanation given for the lower reduction of temperature rise with increased hydrogen pressure is the only one we can offer.

It is gratifying to know that Mr. Thompson confirms the authors' views that end-iron heating limitations will not restrict the development of the large highly-rated machines so far envisaged and also the figure for the reduction in stator heaviest lift when changing the short-circuit ratio from 0·6 to 0·4.

Asynchronous Operation.—In reply to Mr. Casson, there is no advantage in operating existing designs of generators asynchronously except where little or no active power is required. In the event of very low short-circuit-ratio machines being developed, the resultant increase in the steady asynchronous rating would make this mode of operation more attractive.

As Mr. Barker points out, the percentage fluctuation in stator current should be taken into account in any accurate assessment of the asynchronous running limit. The fluctuation is considered, however, to be of second-order effect and an approximate limit of about half-rated load appears to be sufficiently accurate in practice. The reduction in short-circuit ratio improves asynchronous running performance since this means a smaller gap, less magnetizing current and some improvement in the asynchronous torque/slip characteristic. The higher electrical loading might have a negative effect if existing rotor

damper winding designs are adhered to. If the excitation is lost on a highly rated machine, power should be reduced promptly to lower the stator current to rated value, but the practical difficulties of meeting such an emergency with large units operating with advanced steam conditions have yet to be investigated.

In reply to Professor Prescott, the resulting torques occurring during asynchronous running are not large, particularly if the field is open-circuited. Under out-of-step conditions there were no serious disturbances reported from elsewhere on the system, but the effects were noticed at Dunston 'B' power station some five miles away. The values given for the maximum stator active power in Table 7 are peaks of oscillations, as can be seen from Fig. 13(*d*).

Mr. Horsley queries the effect of saturation. We agree that the explanation given in Section 4.3.3 for differences in the damping torque coefficient obtained from small oscillations from the asynchronous torque/slip curve is not entirely satisfactory. The application of field excitation to the rotor, together with the slip frequency current, will result in increased iron saturation in some regions and reduced iron saturation in others. The net result appears to be a smaller asynchronous torque when there is no excitation, but the explanation for this is not obvious. The difference of frequencies in Table 5 is considered to be largely due to the effect of the voltage regulator. The difference in synchronizing torque coefficient in, for example, the first two lines of the Table is very much larger than could be explained by the different generator transformer ratios. The action of the regulator is not, of course, the only factor involved, the angle about which the oscillations occur being of great importance.

Out-of-Step Operation and Self-Synchronizing.—In reply to Dr. Busemann, we would point out that the action of the governing system is complex and depends upon the specific conditions of a particular test. Those at Cliff Quay were fault-throwing tests and that to which reference is made in Section 5.3.3 was an asynchronous running test. We do not consider the statements made in Reference 10 and in the paper are inconsistent. In both tests the action of the governing system has not been clearly elucidated and future work is required on this problem.

With regard to Mr. Powell's comment on the behaviour of governor and boiler controls, we have no doubt that, with similar tests in future, the performance of governor systems will be thoroughly investigated. Heavy valve pumping was not noticed during any of the Stella tests.

The ability of a machine to resynchronize depends upon the per-unit damping and synchronizing torques, and it is quite true, as Mr. Vickers has said, that in the more highly rated machines these are likely to be reduced. If at the same time, however, the short-circuit ratio is reduced this might increase the per-unit damping torque. It may be necessary for manufacturers to adopt special design procedures to improve the asynchronous characteristics of their generators in the future.

In reply to Mr. Baxendale, pole-slipping is not expected to occur with the limiter in use. If this is refuted by further tests or experience a boost from the limiter might be valuable. It would be preferable, however, if the strength of the field varied according to the angular position of the rotor.

The authors thank Mr. Baxendale for the information given in Fig. E and Table A. This emphasizes the wide variety of fault and operating conditions which may have to be taken into account when choosing the optimum settings of generator overcurrent relays.

Replying to Mr. Hore, the 14% voltage drop mentioned in Section 6.3 would occur at the 132 kV busbars.

It is agreed that pole slipping by a number of machines is likely to prove more serious than if only one machine is involved, but the technique suggested for resynchronizing by reducing power applies equally well to a number of machines. It might be necessary at times of widespread system disturbance to shed load concurrently in order to prevent a disastrous drop in frequency.

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DEVELOPMENT OF HIGH-VOLTAGE AIR-BREAK CIRCUIT-BREAKERS WITH INSULATED-STEEL-PLATE ARC CHUTES

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SUMMARY

The paper reports research and development done over the past ten years to investigate the principles of operation of a.c. air-break circuit-breakers for voltages up to 15 kV and breaking capacities up to 500 MVA. Much of the research data on contacts, arc runners, the behaviour and control of arcs in arc chutes and arc extinction is of a fundamental nature and suitable for general application. High-speed photography played an important part in obtaining the data. The arc chute that was finally developed is of the insulated-steel-plate type, but no blow-out coil is used.

The research has been applied to the design and manufacture of air-break circuit-breakers with British ratings up to 250 MVA at 3·3 kV, and up to 500 MVA at 6·6 kV, 11 kV and 15 kV, and American ratings up to 750 MVA. Details of the performance of the circuit-breakers and the effect of the system characteristics are given.

Development is continuing to higher voltages and ratings.

(1) INTRODUCTION

In recent years a good deal of time has been devoted to the development of air-break switchgear for voltages between 3 kV and 15 kV. In the United States, air-break switchgear is used almost exclusively for duties up to 15 kV, while in Great Britain its use has been limited to 3·3 kV for situations where the inherent advantages of oilless circuit-breakers can be usefully exploited, for example for power-station auxiliaries. The arc chutes have been principally of the coil-excited type at the higher voltages. The object of this paper is to describe some recent research and development work which has led to the production of high-voltage air-break circuit-breakers using arc chutes without coils.

The project commenced in 1948 when British air-break circuit-breakers were available for 3-phase ratings up to 150 MVA at 3·3 kV. Its object was to extend the range of voltages up to 15 kV and breaking capacities up to 500 MVA and possibly even higher. To further that object a series of separate researches was done initially on contacts, arc runners and arc chutes, and the performance of existing air-break circuit-breakers was studied in the light of the information obtained. By 1951 it had been decided that an arc chute that consists essentially of a series of spaced insulated steel plates was suitable for a development to higher voltages, and the first 15 kV circuit-breaker with such arc chutes was tested in 1954.[1] The contacts, arc runners and arc chutes have all been developed further since that time, and the construction of a typical present-day circuit-breaker with insulated-steel-plate arc chutes is shown in Fig. 1.

(2) CHOICE OF ARC CHUTE AND RESEARCH PROGRAMME

Air-break circuit-breakers differ fundamentally from each other according to the type of arc chute used. At the beginning of the project there were three main types of chute, namely (i) the bare-metal-plate type, (ii) the all-insulated type with blow-out coil, and (iii) the all-insulated type without blow-out coil. Three circuit-breakers were then available for experiment; an experimental 6·6 kV circuit-breaker with chute of type (i), a 3·3 kV circuit-breaker with chute of type (ii), and a 440-volt circuit-breaker with a chute of type (iii). To decide which, if any, of the basic forms of chute was suitable for development to higher voltages, the characteristics and performance of each circuit-breaker were studied.

The bare-metal-plate arc chute consisted essentially of a series of spaced bare plates of magnetic material on to which the arc rooted and was thereby split into a number of portions in series. It was found that control of the arc before it rooted to the plates was poor, and when rooting took place the series arcs that formed between the plates ran rapidly to the top of the plates and merged into an arc outside the chute, unless the tops were insulated. Further, the arc, instead of running smoothly along the tail portion of the moving contact towards the arc runners, would tend, as the contacts opened, to maintain one root at the point where the arc was initially drawn and the other on the metal plate nearest to that point. Transfer from the moving contact to the runner was then delayed until the moving contacts reached the fully open position, which in a high-voltage circuit-breaker may be several cycles. It was noted that, although chutes of this type were the first developed in the United States for high voltages,[2] their further development appears to have been abandoned in favour of the coil type.

The insulated chute with blow-out coil consisted of a series of spaced, slotted plates of insulating refractory material, the arc being driven into the plate slots by the blow-out coil and an associated magnetic circuit. Control of the arc prior to switching the coil was poor, and the time taken to switch in the coil was variable and sometimes excessive. This latter problem arises from the general requirement that for successful switching-in, the voltage impressed across the coil by the arc shall give a rate of rise of coil current at least as great as the maximum rate of change of the largest current that has to be switched, and a separate chute is sometimes required to obtain this voltage.[3] It was also noted that, at the higher voltages, more than one coil may be required to drive the arc into the chute.[4] The m.m.f. available to energize the coil in this type of chute is almost unlimited and very strong fields can be obtained. However, it was seen that as the arc was lengthened into a zigzag path those parts that lay parallel to the direction of the field experienced no driving force.

The insulated chute without a coil was similar to type (ii), but instead of a coil it had magnetic material outside it, similar in construction to many contactors. In this case the driving field was induced in the magnetic circuit by the arc itself, and although relatively weak the field was available immediately the arc was drawn.

Chutes of less conventional types were also tried on a small

The authors are with A. Reyrolle and Co., Ltd.

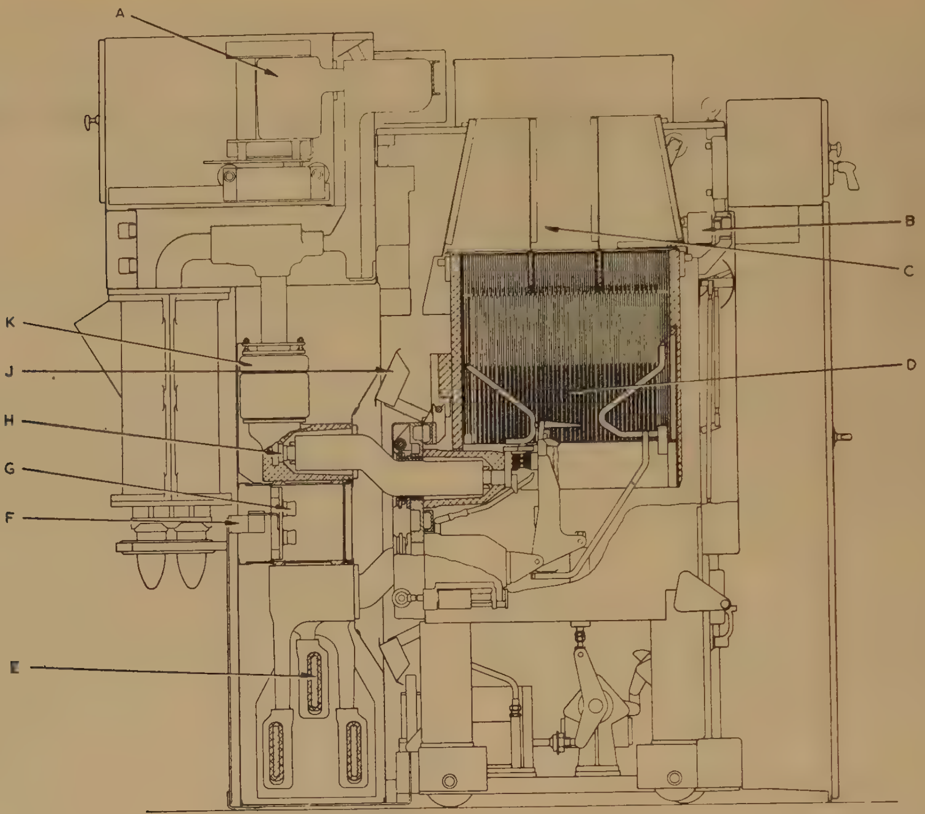

Fig. 1.—11/15 kV air-break panel with insulated-steel-plate arc chutes.

A. Voltage transformer.
B. Secondary contacts.
C. Roof barriers.
D. Arc chute.
E. Busbar chamber.
F. Earth bars.
G. Earthing contacts.
H. Plug isolating contacts.
J. Locking-off doors.
K. Current transformers.

scale. One had moving parts to 'chop' the arc, another had a store of sand to be poured on to the arc and a third was fitted with permanent magnets. Sometimes the emphasis was on lengthening the arc, at other times on cooling it. In general, experiments showed that lengthening the arc in an air-break circuit-breaker was easier and more effective than trying to achieve intensive cooling.

After considering the results of all these experiments it was concluded that a chute of simple construction having plates of insulating material but without a blow-out coil would be most suitable for further development, provided that an efficient arc-energized magnetic circuit could be devised. The basic disadvantage of using magnetic material outside the chute is that the air-gap is large, being equal to the width of the chute. A decision to place magnetic material inside the chute by embedding it in the plates of insulation led to the introduction of the insulated-steel-plate type. The behaviour of the first experimental chutes of this type was so successful that work on other forms was eventually suspended.

During this investigation into basic arc-chute types, research was already in progress on items of equal importance to the project as a whole. The programme included the following items.

(*a*) *Contacts.*—Normal load and short-circuit rating. Contact materials. Blow-off and blow-on forces. Sliding and rolling contacts. Contact making and breaking. Contact bounce. Current transfer from main to arcing contacts. Influence of waveform and frequency.

(*b*) *Arc-runners.*—Effect of material and form of the runners on the speed of motion of the arc. Effect of a transverse magnetic field. Current transfer from contacts to runners. Erosion of runners by the arc.

(*c*) *Arc-chutes.*—Relative efficiencies of arc cooling, arc lengthening and arc splitting. Effect of magnetic fields. Aerodynamic effects. Switching-in of field coils. Insulating and magnetic materials.

(*d*) *Arc Extinction.*—Effect of arc voltage on circuit recovery voltage. Measurement and evaluation of current-zero phenomena in a.c. circuits.

Some of the above items are reported at length and others more briefly.

(3) INSULATED-STEEL-PLATE ARC CHUTES

(3.1) Principles of Operation

The insulated-steel-plate arc chute shown in Figs. 2 and 3 comprises a number of slotted plates closely spaced inside an insulating box which is open at top and bottom. Each plate consists of a $\frac{1}{16}$ in thick sheet of magnetic steel moulded and completely embedded inside two $\frac{1}{8}$ in thick mica-and-glass sheets.

The arcing contacts are arranged to initiate the arc above the bottom of the slots so that a magnetic field is established before the arc is drawn. This, together with the runner configuration, drives the arc up the chute, where it is moved into the inclined portions of the slots by the action of the steel sheets. There the arc is lengthened by being forced to follow a compact zigzag path and is cooled by the plates and the surrounding air. At currents above the load-current range the arc lengthens very quickly and the arc voltage builds up with corresponding rapidity. Arc

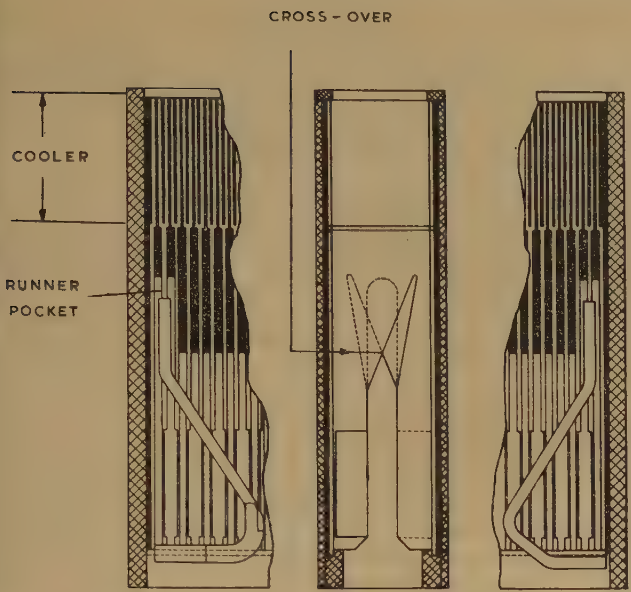

Fig. 2.—Sections of an insulated-steel-plate arc chute.

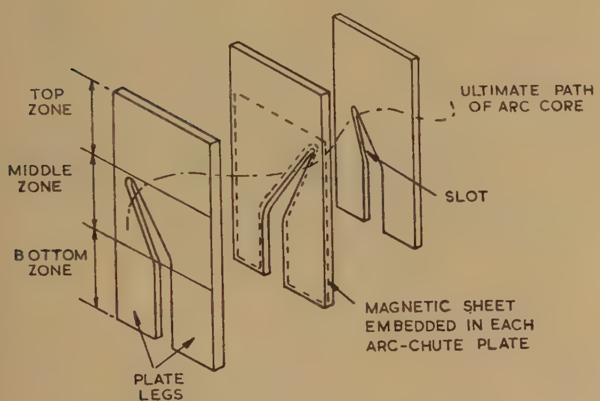

Fig. 3.—Exploded view of arc-chute plates.

voltage serves as a practical guide to the performance of the circuit-breaker, and near the limit of performance the arc is usually extinguished if the average arc voltage reaches about 30% of the peak recovery voltage. The arc voltage modifies the waveform of the current considerably, and except for some asymmetrical currents it reduces the instantaneous recovery voltage, i.e. the recovery voltage at the time of arc extinction, to a value less than the peak, as shown in Fig. 19(*a*).

Arc extinction is achieved because the arc resistance at current zero is high enough and is increasing at a rate fast enough to prevent the continuance of power-frequency currents. Except at currents of the order of amperes, the arc resistance is nevertheless low enough to damp the system restriking voltage sufficiently for it not to appear as a major electrical stress across the circuit-breaker after arc extinction; i.e. extinction occurs with the thermal clearance and appreciable post-arc conductivity typical of most air-break circuit-breakers.[5] The energy input into the arc during the flow of post-arc current depends mainly on the instantaneous recovery voltage, which is thus the main circuit severity factor.

(3.2) Arc-Chute Plates

The plate may conveniently be divided into three zones (Fig. 3):

(i) The bottom zone, containing the parallel-sided portion of the slot through which the arcing contact passes and which accommodates the sloping portion of the arc runners. This is designed so that the steel is as close to the arcing contacts and runners as mechanical considerations allow.

(ii) The middle zone, where the arc is elongated between the plates by means of staggered slots. The arc burns for the greater part of its life in this zone, where the magnetic field is strongest and the space available for the arc to be lengthened is as great as possible. The boundary between the bottom and middle zone is the 'cross-over'.

(iii) The top zone, where the arc is allowed to lengthen further by looping upwards and where the gas is deionized sufficiently to prevent restrikes across the top of the chute.

(3.3) Plate Spacing

The plates are spaced apart by fluted side-sheets, and the optimum spacing between plates varies with the size of the chute. For chutes small enough to be used at low and medium voltages, $\frac{1}{8}$ in spacing is adequate; for the larger high-voltage chutes $\frac{3}{16}$ in spacing has been found to be necessary and sufficient.

(3.4) Insulating Materials

The original tests were made with moulded asbestos at voltages of about 1 kV. The performance of chutes using this material got worse after each test and its use was discontinued.

Of the ceramics that were available, even those of the highest grade were cracked by the heat of the arc, although it should be noted that the special ceramics now used for circuit-breakers in the United States[6] were not available at the time.

Moulded mica-and-glass materials were then tried and found to withstand the effects of the arc admirably, with negligible deterioration after a great number of shots at the largest currents and voltages. Originally, moulded mica-and-glass of the sizes required was available as flat plates. A steel plate was sandwiched between pairs of these cut to the required shape, and the whole cemented together with a household refractory cement. These plates were prone to splitting due to mechanical and thermal shock, but later techniques have permitted the steel to be moulded in mica-and-glass, resulting in a much stronger plate.

The original refractory cement withstood the arc so well (although not as well as the moulded mica-and-glass) that experiments were made with steel sheets coated with different refractory cements. They were all found suitable for use in low-voltage chutes. The electric strength of such coated plates was improved by undercoats of high-electric-strength varnishes, but the relatively low surface resistivity made them unsuitable for voltages above 3·3 kV.

None of many other materials tried was as good as moulded mica-and-glass, which was used for the majority of research and development tests and in production.

Perspex was used originally for one of the fluted side-walls of the chute instead of moulded mica-and-glass so that the arc could be photographed. The Perspex withstood the arc so well in this position and was so much better mechanically and electrically than the other side-sheet that both are now made of this material.

(3.5) Magnetic Circuit

The magnetic sheets are similar in shape to the mica-and-glass sheets and form a tight magnetic loop around an arc drawn in the slots. The magnetizing force in the slot is approximately inversely proportional to its width.

Fig. 4 shows measured values of flux density in part of a typical chute with plates at correct spacing but stripped of insulation to leave room for search coils. The arc was simulated by a con-

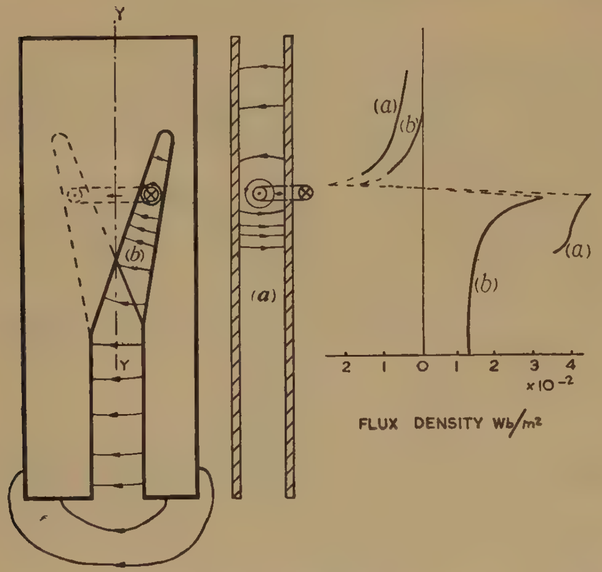

Fig. 4.—Measured values of flux density for part of a typical arc chute.

(a) Flux density normal to adjacent plates along YY.
(b) Flux density across the slot.

ductor carrying 1 000 amp. Since a relatively strong magnetic field exists between the middle zones of adjacent plates, those sections of a tortuous arc column that lie parallel to the plane of the plates are urged into the chute and tend to bow upwards beyond the top of the slots. This feature permits full use to be made of wide chute plates in contrast to the limitations of coil-excited chutes.

The narrow neck of steel near the top of the slot saturates at about 1 000 amp; thus at currents less than this the forces acting on the arc are proportional to the square of the current but at larger currents they are proportional to the current.

Different grades and thicknesses of magnetic material have been tried, but they appear to have little influence on the performance. This is probably because before saturation occurs the thickness of the magnetic sheet has a negligible effect on the reluctance of the air-gap, while at large currents the field produced by the natural loop of the arc inside the chute is more significant than that provided by the magnetic circuit.

(3.6) Cooler

The 'cooler' is that part of the top zone of the chute used to deionize exhaust gases; it is formed by adding insulating plates. In Fig. 2, each $\frac{3}{16}$ in exhaust path is split into two parallel paths having $\frac{1}{8}$ in spacing; this results in increased cooling due to the reduced spacing and larger cooling surface.

The impedance of the cooler to air flow determines the effectiveness of the cooling and is governed by the element spacing and length. In a low-impedance cooler, one where, for example, the spacing is greater than $\frac{1}{16}$ in, the arc gases which emerge are not always sufficiently deionized to ensure that an arc does not strike (*a*) across the top of the chute, (*b*) between phases, or (*c*) to any earthed metal of the circuit-breaker enclosure. A roof barrier is therefore fitted which divides the space above each chute into a number of compartments which further segregate and deionize the gases before they are allowed to mix or come into contact with earthed metal. The exhaust gases eventually pass out of the cubicle through a metal-gauze ventilator. If a high-impedance cooler is used the roof barrier can be omitted, but there is a tendency for such a cooler to hold the arc low down in the chute.

(4) CONTACTS

(4.1) General

The design of the contacts shown in Fig. 1 was based on work included in the research programme outlined in Section 2. The more important results of this work are given and serve to justify the contact arrangement finally adopted.

(4.2) Short-Circuit Current-Carrying Capacity

The short-circuit current-carrying capacity of a contact depends only on the contact material and the resultant of the forces acting on the contact. There are three such forces: (i) the mechanical load on the contact, (ii) the electromagnetic force due to the interaction of the current in the movable contact member with the magnetic field produced by other current-carrying conductors, and (iii) the blow-off force due to the current constriction. Contrary to beliefs held by many engineers, practical circuit-breaker contacts are such that, at currents above their rating, welding occurs by melting rather than by blow-off in 50 c/s circuits, i.e. the sum of forces (i) and (ii) (hereafter called the total external force) is greater than force (iii) for such contacts at all currents up to that at which welding occurs. (This is not necessarily so for bolted contacts, which have loadings higher than those considered here.)

Fig. 5 shows the results of 50 c/s tests on butt contacts with

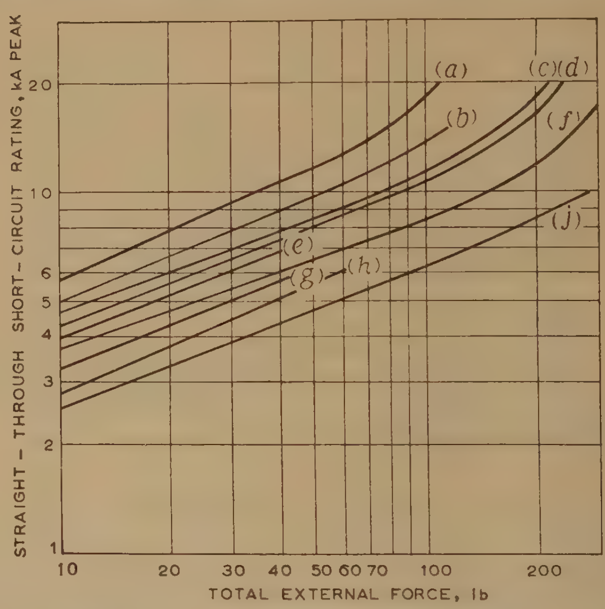

Fig. 5.—Experimental relation between straight-through short-circuit current rating and total external force for butt contacts of various materials.

(a) Copper.
(b) Silver-plated copper.
(c) Tinned copper.
(d) Copper/gunmetal.
(e) Copper/tungsten-copper.
(f) Silver/gunmetal.
(g) Silver/tungsten-copper.
(h) Tungsten-copper.
(j) Gunmetal.

hemispherical ends, which have only one real area of contact. The effect of the blow-off due to current constriction is covered automatically in Fig. 5, because it depends only on current and external force. Peak current is used for the ordinates because the time-lag between the temperature at the real area of contact and the current was small in all tests, and welding always occurred in the first few loops of currents. This time-lag was estimated from the voltage across the contacts. With total external loads less than about 100 lb, if welding did not occur during the first major loop of current it did not occur during any following loop. The 'melting voltage', i.e. the voltage across a

contact when it starts to weld, was found to conform approximately to that predicted by the steady-state theory for untarnished contacts[7] for all the metals tested. Normal tarnish films do not therefore affect the results.

(4.3) Main Contacts

It follows from Fig. 5 that, for a given total load on the contacts, a number of relatively lightly loaded contact-members with the current evenly distributed among them are better for preventing welding than one heavily loaded member. For this reason the main current-carrying contacts in the circuit-breaker of Fig. 1 are of the multi-finger type, each loaded with about 10 lb. They are made of silver-plated copper, the advantages of which for normal current-carrying are well known; their advantages for carrying short-circuit currents can be judged from Fig. 5.

(4.4) Arcing Contacts

The current is transferred from the main contacts to arcing contacts before the arc is drawn. Because the position of arc initiation has a marked effect on the circuit-breaker performance these contacts are arranged to initiate the arc inside the magnetic circuit.

The arcing contacts are butt contacts arranged to be of the blow-off type. They inherently bow the arc up into the chute because of the tight current loop which is formed and can be made to fit easily into the narrow parallel-sided slots of the bottom zone. A disadvantage of the long arcing contacts is that a large transfer impedance exists between them and the main contacts and it is necessary at the larger short-circuit currents to introduce an intermediate contact. Even so, some arcing inevitably occurs at the main contacts during transfer. Its duration depends upon the speed of break of the main contacts, the inductance of the transfer loops and the instantaneous current to be transferred. The effects of arcing on the current-carrying portions are minimized by using knife-blade main contacts which do not break finally on the normal current-carrying surfaces.

(4.5) Arc Initiation

When the arc is first struck at the arcing contacts it is short and relatively immobile because it cannot bow appreciably under the action of the magnetic field. Movement of the cathode root depends to some extent on the heating of the electrode surface ahead of the root by the arc column, and the arc does not move quickly until the arc length increases sufficiently to make bending possible. To minimize erosion the arcing contacts should open quickly and the arc should be moved quickly from them. The initial speed of break of the circuit-breaker of Fig. 1 is about 15 ft/s, and initial arc movement is increased by the strong local field produced by the tight current loop. Erosion is also reduced by tipping these contacts with sintered tungsten-copper; this has been found necessary to ensure that the arcing contact leads the main contact (or intermediate arcing contact) by an amount which remains reasonably constant.

(5) ARC RUNNERS

(5.1) Material and Configuration

The roots of relatively long arcs tend to drag behind the arc column, and the choice of a suitable runner material was based initially on tests at relatively small currents to determine the effect of the runner material on this drag. For the tests the runners were parallel and supported in a vertical position between two flat rectangular coils separately excited from a d.c. supply. The results are shown in Fig. 6. For materials other than steel the runners were of rectangular section 1 in wide by

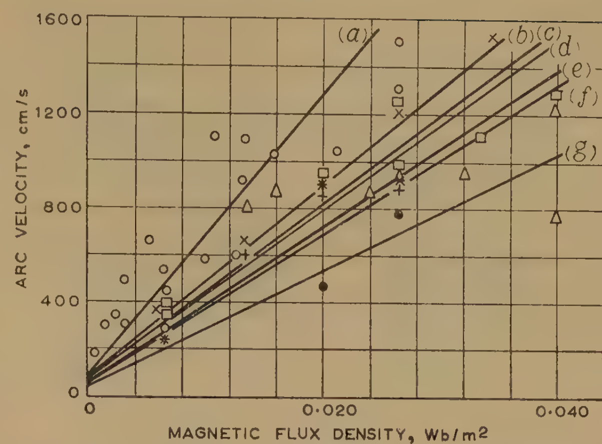

Fig. 6.—Variation of arc velocity with flux density and electrode material for low-current d.c. arcs.

○ (a) Copper.
× (b) Tungsten-copper.
□ (c) Aluminium.
+ (d) Steel.
△ (e) Brass.
∗ (f) Lead.
● (g) Carbon.

$\frac{1}{8}$ in thick and arranged so that the arc ran up the broader side. The steel runners each consisted of 6 laminations of 0·14 in Stalloy, spaced $\frac{1}{16}$ in apart by brass washers and arranged at right angles to the magnetic field so that the arc roots ran up the edges of the laminations and the magnetic flux acting on the arc was not excessively distorted by the steel. The brass runners were polished, because otherwise the arc remained almost stationary on them. It was concluded that the drag was least for copper and greatest for higher-melting-point materials such as tungsten and carbon. Other tests showed that the arc ran more consistently along sharp edges, so copper runners of rectangular section are used.

Steel runners were tried as an alternative to copper in full-scale a.c. tests of a circuit-breaker. The arc ran slightly more quickly on steel than on copper, but at 43 kA the sparks thrown off from the steel were considered excessive and this resulted in the continued use of copper.

The configurations of typical runners are shown in Figs. 1 and 2. To achieve high arc velocities the sloping portions should be as steep as possible, but runners with an angle of 35° to the horizontal have been used successfully. Space must be provided between the cross-over and the sloping part of the runner to allow the arc root to move round the upper bend on to the top of the runners; otherwise the arc strikes down to the runner in this region.

If the chutes are hinged at the fixed-contact side so that they can be raised easily, the vertical portion of the runner cannot be taken above the cross-over level in the chute; its top is then heavily eroded and the copper is thrown into the chute and across the insulation below. An arc-resisting tip eliminates this difficulty, but the increased thermionic emission at this point at a current zero affects the performance of the chute. It is better to end the runners in pockets at the ends of the chute (Fig. 2), thus limiting the emission of copper.

(5.2) Transfer of Arcs from Arcing-Contacts to Runners

During the opening of the contacts the arc moves along the tail attached to the moving contact until it makes contact with the runner on the moving-contact side. A root is formed on the runner as shown in Fig. 7, and the part of the arc column between this and the root on the moving contact is extinguished by the shunting action of the link from the runner to the moving contact. When the moving contact carries an anode root, imme-

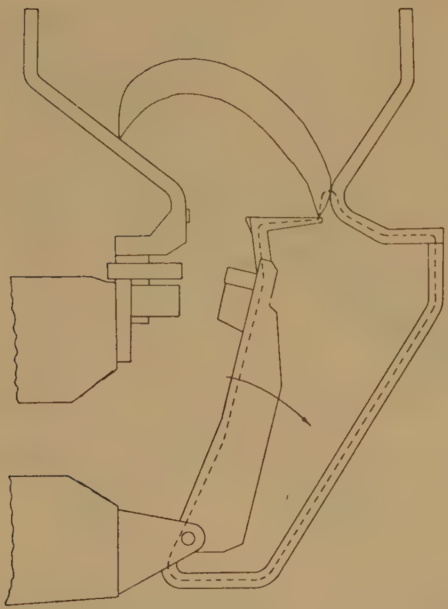

Fig. 7.—Arc transfer from arcing contact to runner.
---- Transfer circuit.

diate rooting occurs because a new anode is easily formed. To form a cathode root, the new root area must be heated to a temperature high enough to emit electrons, and a sufficiently high voltage must exist between the runner and the arc column in contact with it. The larger the current, the lower is this voltage. When the new root is formed, transfer of current from the shunted arc column to the new root is delayed by the inductance of the transfer circuit, but the time of transfer is usually small and currents of several kiloamperes are transferred in less than 1 millisec.

If the link is omitted, two new roots must be formed and the voltage between two points of the arc column in contact with the runner must exceed the sum of an anode and a cathode root-drop. A short series arc is then formed between the moving contact and the runner. This burns low in the chute and causes trouble, and it is mainly for this reason that a link is used.

The arc travels back along the tail of the moving contact faster than the moving contact opens. This permits the time from arc initiation to transfer to the runner to be a minimum, and reduces erosion at the point of break. The tail also acts as a shield to prevent the arc from moving down the back edge of the moving contact to a position below the chute.

(6) BEHAVIOUR OF ARCS IN THE ARC CHUTE

(6.1) General

The behaviour of arcs has been judged from a few ultra-high-speed ciné films, several thousand high-speed ciné films and many more oscillograms. Most of the ciné films were taken by photographing through one of the Perspex side-walls. In some special tests, material cut from the arc-chute plates has been replaced by Perspex and photographs taken looking into one end of the chute; in others, the arc has been photographed stereoscopically in mirrors below the chute. Photographs and oscillograms are now so well correlated that much of the behaviour of the arc can be judged accurately from oscillograms only.

In the chute the arc is at approximately atmospheric pressure; its positive column determines its characteristics and appears as a bright discharge with a brighter core somewhere inside. The cross-sectional area of a 200 amp discharge is estimated from the photographs to be about 5 cm^2, and it travels upwards in the bottom zone at an average speed of about 20 ft/s; for a 40 000 amp arc the figures are about 60 cm^2 and 600 ft/s.

(6.2) The Formation of New Arc Cores

At large currents the initial arc velocities are so great that the core of the arc may reach the cross-over in less than a millisecond after contact separation. An appreciable arc voltage is built up across a small contact gap and a new and shorter core forms at the arcing contacts and moves up the chute as the old core dies out (Fig. 8). This may occur repeatedly and give a saw-toothed

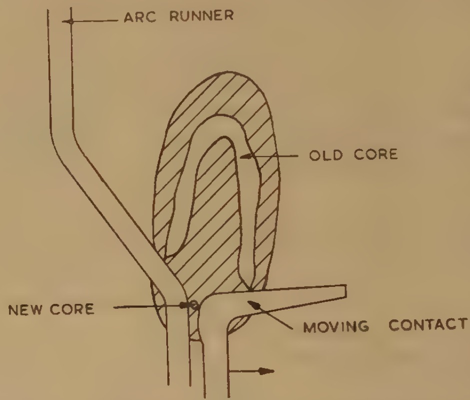

Fig. 8.—Formation of a new arc core during the early stages of contact separation.

arc-voltage record immediately after arc initiation. If the initial arc movement is not sufficiently controlled, i.e. if the arc-initiation point is not sufficiently far inside the chute, part of the discharge may spread downwards from such a new arc core and a further completely uncontrolled arc core may form below and outside the chute.

The progress of the arc may be checked at the cross-over if an attempt is made to change its path too abruptly from a straight to a zigzag one. When the arc core initially enters the middle zone much of the discharge may still be following a straighter and shorter path in the bottom zone (Fig. 9). The upper portion of the arc is cooled more by its greater contact with the chute plates and is also suddenly lengthened. The resistance of the upper part of the discharge increases relative to that of the lower part, and the current tends to re-establish in the bottom zone. This process, repeated several times as the

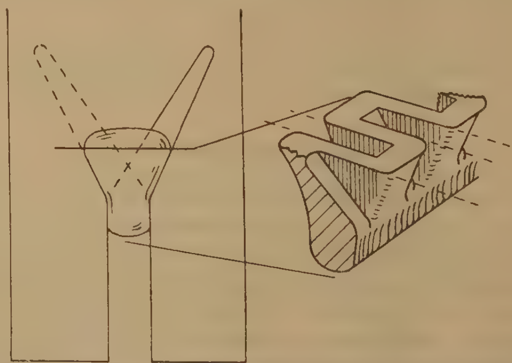

Fig. 9.—Diagram showing why the current tends to concentrate in the bottom zone when the arc is at the cross-over.

arc passes the cross-over, appears as a ripple on the arc-voltage oscillogram lasting for about 1 millisec. The effect varies with the width and slope of the slots and with current.

A similar but more pronounced process can occur as the arc core rises in the middle zone. A new, shorter core can be established several inches lower than the existing one (Fig. 10) and the two cores exist simultaneously for a moment. The time

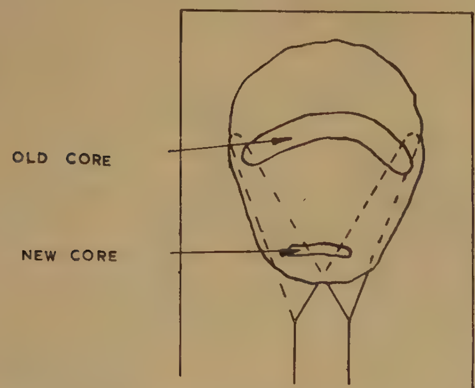

Fig. 10.—Formation of a new arc core in the slots.

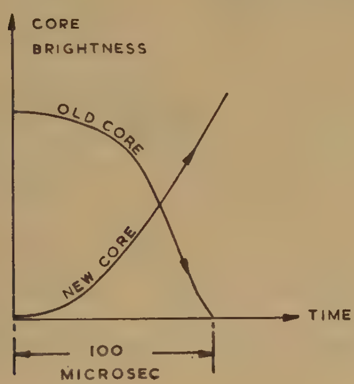

Fig. 11.—Brightness/time curves during the formation of a new core in a 200 amp arc.

for one core to die out and another to attain full brilliance is measured in microseconds. Fig. 11 shows brightness/time curves during the formation of a new core in a 200 amp arc. The formation of new cores in the middle zone can produce relatively large changes in arc voltage and probably accounts for most of the fluctuations in the arc-voltage waveform.

(6.3) The Formation of Branches to the Arc Core

The arc, besides forming a new core, may also form a branch extending from an existing core. The branches described in this Section probably occur in all chutes of the insulated-plate type. Their behaviour has a marked effect on the performance of chutes and they have been studied extensively. The formation of such branches has been photographed at framing rates up to 500 000 frames/sec, and particular attention has been paid to branches, called downstrikes, formed vertically downwards to the moving contact or to a runner. When a downstrike is established, the longer arc in parallel dies away rapidly and the process appears on oscillograms as a sudden reduction in arc voltage.

Downstrikes occur after the arc column reaches the cross-over and are more prevalent if the arc is held there. High-speed photographs show that, during this period, faint streamer-like discharges move down rapidly from the arc core. When a downstrike occurs, it forms along the path of a streamer which has impinged upon the moving contact or part of a runner. The process is illustrated in Fig. 12. A streamer extending from *b* to *d* is subjected to the same voltage as exists from *b* to *c*, and the arc core may form a branch from *b* to *d*. The voltage impressed across the streamers is greatest near the middle of the chute, and most downstrikes occur in this region, striking to the tail of the moving contact. When the downstrike is established the longer tortuous arc between *b* and *c* dies out. A typical streamer from a 9000 amp arc at the cross-over travelled 10·4 cm vertically down to the moving contact in 420 microsec (an average speed of 250 m/s) and caused a downstrike to be initiated along its path to the moving contact 40 microsec after the streamer had reached the contact. The downstrike reached full intensity less than 5 microsec after breakdown along the streamer path.

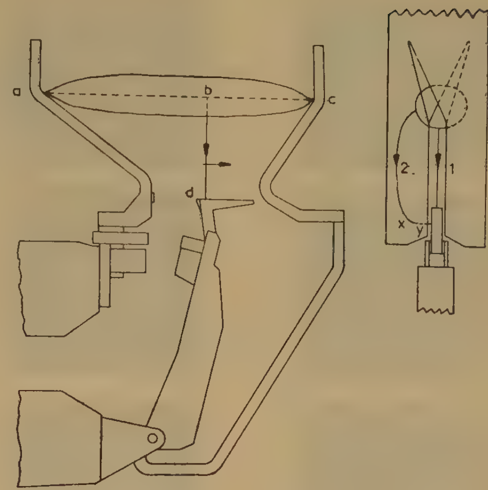

Fig. 12.—Initiation of a downstrike to the moving contact.

(6.4) Controlled and Uncontrolled Downstrikes

Downstrikes, established between the legs of adjacent plates, near the chute walls, sometimes led to failure of the circuit-breaker. A downstrike in this position (path 2, Fig. 12) could be locked between the legs of adjacent chute plates and pressed against the side wall of the chute for several milliseconds, during which only part of the chute was employed effectively. Fig. 13 is a 1000 frames/sec ciné film of such a downstrike. The part *xy* (Fig. 12) could be moved further down by the electromagnetic force of its own loop during the time the downstrike was locked, and this sometimes resulted in an uncontrolled arc forming below the chute.

Downstrikes were controlled by partially blocking the spaces between the chute-plate legs by baffle plates, as shown in Fig. 14. The small gaps shown in the diagram prevent a continuous conducting path being formed across the chute due to deposited copper vapour. With this construction downstrikes do not occur between the legs of adjacent plates and there is no tendency for the arc to spread below the chute. Downstrikes can only form down the 'tunnel' (path 1, Fig. 12) and are forced back into the middle zone of the chute by the electromagnetic forces, in times of the order of several hundred microseconds.

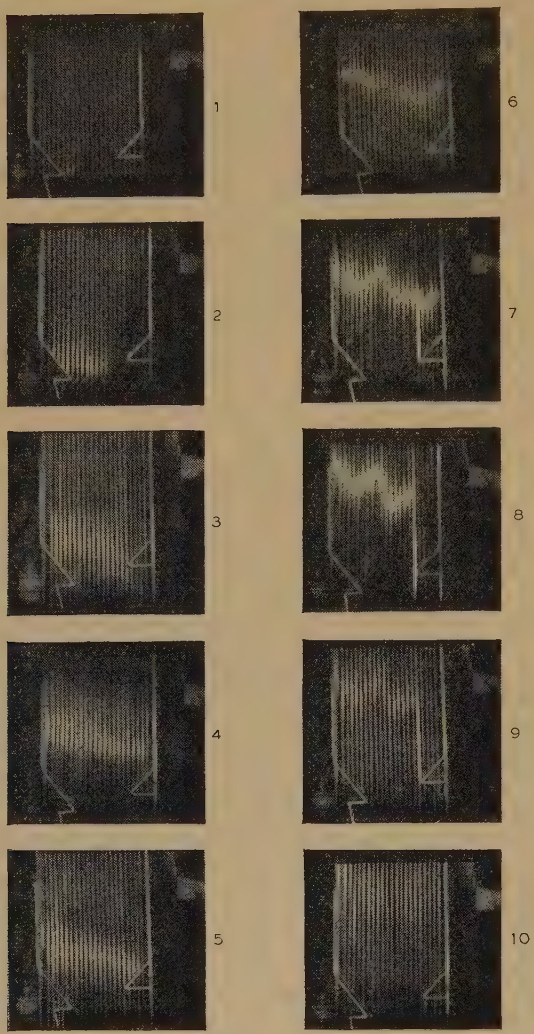

Fig. 13.—1 000 frames/sec film of a downstrike to an arc runner.

(7) CIRCUIT-BREAKER CHARACTERISTICS

(7.1) Time/Current Characteristic

An arcing-time/current characteristic is shown in Fig. 15. The general shape can be predicted from experimental curves showing the variation of current with (*a*) the voltage gradient along the arc column, and (*b*) the rate of arc lengthening. The voltage gradient is inversely proportional to a fractional power of the current, while the rate of arc lengthening is roughly proportional to the square of the current.

The current associated with the maximum arcing time is usually referred to as the 'critical current'. At currents less than this the rate of arc lengthening is small, but by virtue of large arc-voltage gradients, extinction can occur at relatively small arc lengths and short arcing times. At currents above the critical value, a longer arc is necessary for extinction, but the higher rate at which the arc is lengthened eventually reduces the arcing time to less than two loops. The low-current arcs are moved more rapidly into the chute by an air puff which is delivered into the chute from below the contacts after they have parted. By this means critical-current arcing times of 20 or more loops can be reduced to between 4 and 12 loops.

(7.2) Voltage/Current Characteristic

The characteristic which shows the voltage/current limits of performance of an insulated-steel-plate arc chute is illustrated

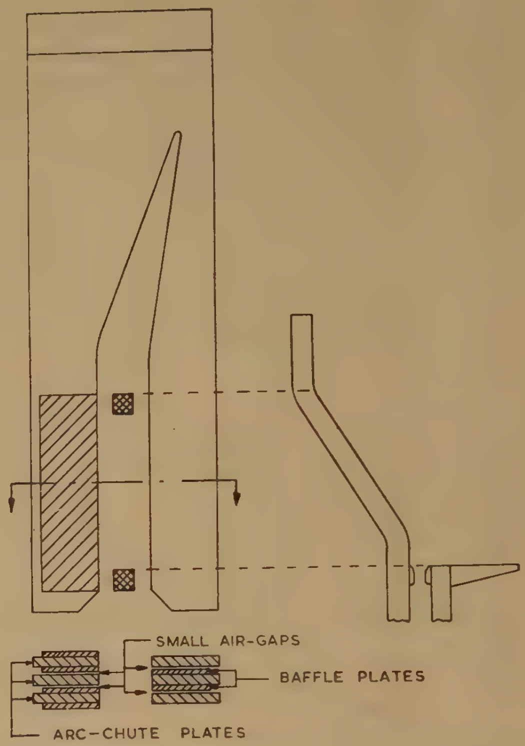

Fig. 14.—Baffle-plate arrangement to prevent uncontrolled downstrikes.

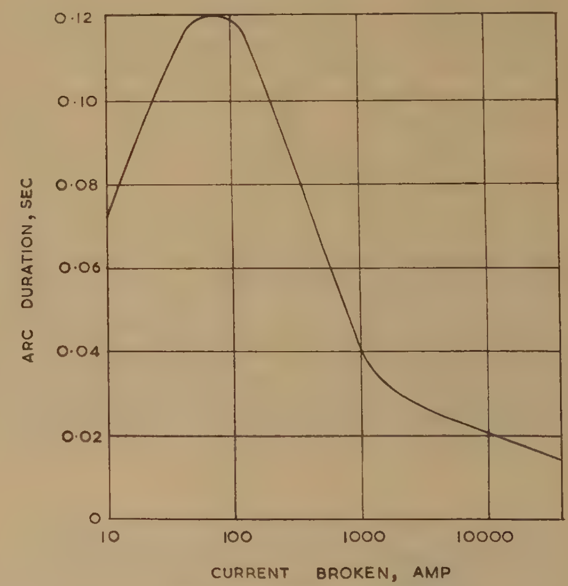

Fig. 15.—Arcing-time/current characteristic for a 15 kV circuit-breaker.

The time is from contact separation to clearance of the third phase.

in Fig. 16. Near the limit of performance the instantaneous recovery voltage for symmetrical currents is approximately proportional to the r.m.s. recovery voltage.

When a short-circuit-current arc is burning steadily in the chute it has a mean zigzag path somewhere in the slots. As a current zero is approached the arc core diminishes and the mean path moves further up the chute. The position of the residual-

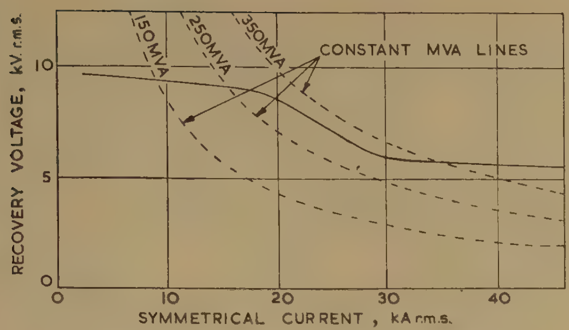

Fig. 16.—Voltage/current characteristic.

arc path during the post-current-zero period when the instantaneous recovery voltage is established across it mainly determines the clearance or failure of the chute.

(*a*) Up to 20 kA the residual arc path is near the top of the slots and reignitions producing failure occur because the maximum zigzag arc path is too short to withstand more than a certain recovery voltage. The chute therefore has approximately a constant voltage performance.

(*b*) In the range 20–30 kA the mean arc path is low down in the slots. The residual arc path will not move to the top of the slots because of the retarding effect of the greater amount of ionized gas that must escape from the chute. This path therefore becomes lower in the slots as the breaking current increases; thus failures occur at a recovery voltage which decreases as the current increases. In this range the chute has approximately a constant MVA performance.

(*c*) Above 30 kA the mean arc path will be at the cross-over level or below and the residual-arc path may only just be in the slots. The movement of the residual-arc path up the chute will be slow, and further increases in breaking current will block the chute more without affecting the mean arc path. In this range, therefore, the chute has approximately a constant voltage performance.

(7.3) Arc-Energy/Instantaneous-Recovery-Voltage Characteristic

An analysis of a great number of 3-phase symmetrical and asymmetrical short-circuit tests on chutes differing in length, width and height has led to an arc-energy/instantaneous-recovery-voltage characteristic for insulated-steel-plate arc chutes (Fig. 17). This shows three zones—reignition, clearance and

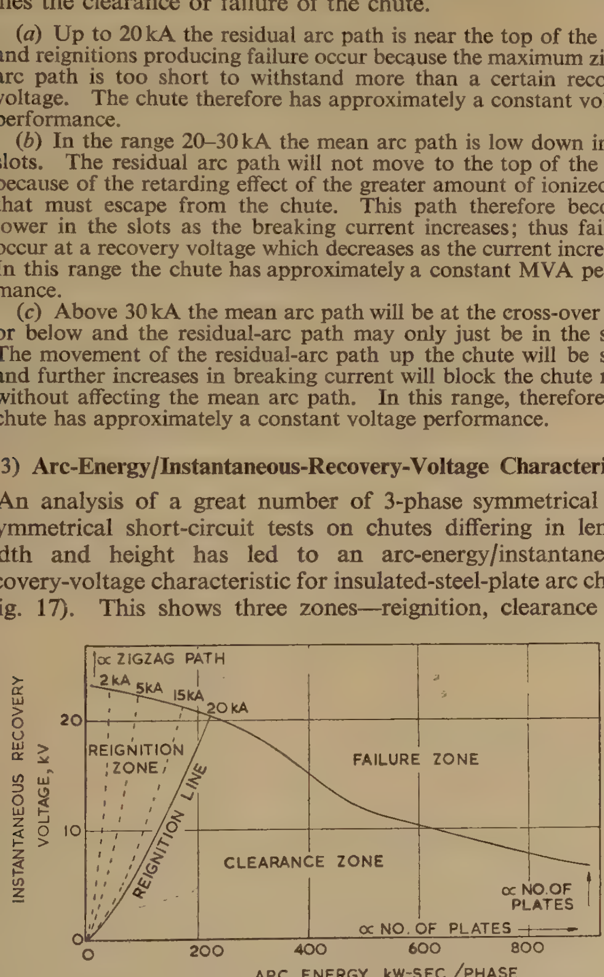

Fig. 17.—Arc-energy/instantaneous-recovery-voltage characteristic.

failure—with boundary lines between reignition and clearance dependent on the current broken.

At a current zero, if the arc is not far enough up the chute to withstand the instantaneous recovery voltage, reignition occurs and arcing continues until a more favourable condition for clearance arises. At the next current zero, if the arc energy lies in the clearance zone for a particular phase, this phase will withstand the recovery voltage, and the two other phases will clear later. The clearance of the other phases is generally easier, because, although the arc energies are greater, the recovery voltages are much less than those of the first phase to clear, which has been subjected to a 1·5 times factor. If the arc is as far into the slots as possible and still unable to withstand the instantaneous recovery voltage, its arc energy lies outside the clearance zone and failure occurs. Two typical oscillograms, each showing a reignition prior to clearance, are reproduced in Fig. 18. Fig. 18(*a*) is for reignition in the middle of the reignition

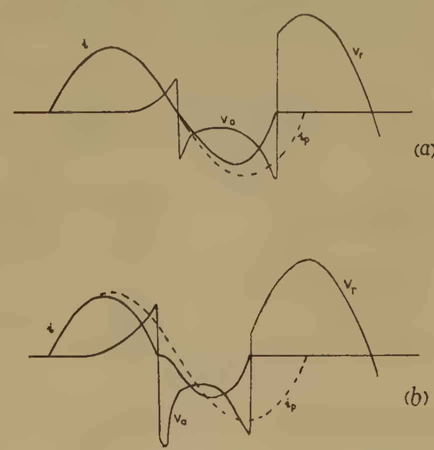

Fig. 18.—Typical oscillograms showing reignitions prior to clearance.

(*a*) Reignition in the middle of the reignition zone.
(*b*) Reignition close to the reignition line.
v_r = Recovery voltage. i = Current.
v_a = Arc voltage. i_p = Prospective current.

zone, and Fig. 18(*b*) is for reignition close to the reignition line. The arc extinctions lie in the clearance zone, their position depending on the severity of the duty.

If the chute is near the limit of its performance and is breaking asymmetrical currents, extinction occurs near the top of the clearance zone, where the arc energy bandwidth is at its narrowest. When the chute is well within its capabilities, very heavy suppression of the current can occur, and the instantaneous recovery voltage is therefore greatly reduced and may sometimes be on a falling voltage. This heavy suppression is only seen on single-phase interruptions and on the second and third phases to clear of a 3-phase current interruption.

The arc-energy scale is approximately proportional to the number of plates. At the high-arc-energy end of the scale the instantaneous recovery voltage is also nearly proportional to the number of plates, because the residual-arc path is just above the cross-over. At the lowest arc energies the instantaneous recovery voltage that can be withstood is approximately proportional to the length of the available zigzag path of the arc, because at these currents the arc is fully stretched.

(8) CIRCUIT-BREAKER PERFORMANCE

(8.1) Load Currents

The arcing times at load currents (0·8 power factor) are generally similar to those for corresponding currents at low power factors, and since the critical current of air-break circuit-breakers normally lies in the load-current region, arcing times during normal load switching operations may be 0·04 sec or more.

(8.2) Short-Circuit Currents

(8.2.1) General.

Over most of the short-circuit range, arcing times are very short and a total break time of less than 3 cycles can be obtained

from rated normal current to rated short-circuit current. Arc energies of the order of a megawatt-second may be expended when clearing the largest currents, giving a characteristic flash of reflected light and a high noise level.

(8.2.2) **Asymmetrical Currents.**

The larger arcs which may occur during the clearance of asymmetrical currents tend to overfill the chute and impose a more severe duty on an air circuit-breaker, not only because of the larger arc energies generated but also because the instantaneous recovery voltage may be higher.

Fig. 19 compares the performance of an air circuit-breaker and

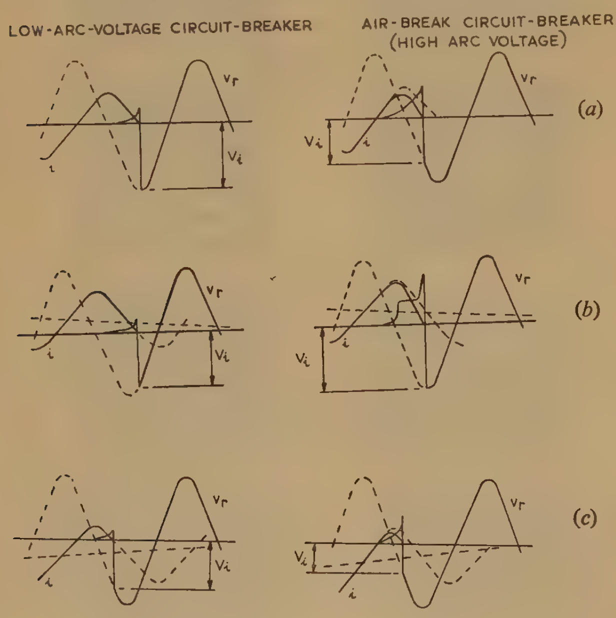

Fig. 19.—Comparison of instantaneous recovery voltages for a low-arc-voltage circuit-breaker and an air-break circuit-breaker.
(*a*) Symmetrical currents.
(*b*) Asymmetrical currents (major loop clearance).
(*c*) Asymmetrical currents (minor loop clearance).
v_r = Recovery voltage.
v_i = Recovery voltage at arc extinction.
i = Current.

a circuit-breaker having a low arc-voltage characteristic when switching identical currents at the same power factor and point of contact separation. It will be noted that the instantaneous recovery voltage for a low-arc-voltage circuit-breaker when switching symmetrical currents is approximately the peak phase voltage, while for the air circuit-breaker it is something less owing to the current being forced to a premature zero. For asymmetrical currents on major loop clearances it is the air circuit-breaker which is subjected to an instantaneous recovery of the peak phase voltage.

Therefore when clearing the major loop of an asymmetrical current the instantaneous-recovery-voltage severity is a maximum and the ratio of asymmetrical to symmetrical severity is greater for air-break circuit-breakers than for those which have a low arc-voltage characteristic.

(8.2.3) **Live and Dead Blade Severity.**

In the short-circuit testing of air circuit-breakers with contacts arranged unsymmetrically it is required by specification that the supply be connected to the side of the circuit-breaker which gives the more onerous condition. When a circuit-breaker such as that of Fig. 1 clears short-circuit currents the largest quantity of gas is generated at the fixed-contact side of the chute because there is no arc transfer to the runner at that side, and the arc moves more quickly up and burns for a longer time there. Earthed metal in metalclad constructions is approximately the same distance from all points at the top of the chute, and therefore with a low-impedance cooler the possibility of earth faults when the circuit-breaker is opening is greater when the fixed contact is connected to the supply side, i.e. a dead-blade connection.

With high-impedance coolers, gases cannot escape so easily and there is a greater tendency for the ionized gases to move down the chute and to stress the insulation between the fixed and moving contacts. This may cause further breakdown across the contact gaps until failure to earth below the moving contact blade takes place. With high-impedance coolers, therefore, the circuit-breaker is generally more highly stressed during live-blade tests.

(8.3) Low Inductive Currents

When transformer magnetizing currents in the range 5–200 amp were switched at 11 kV no appreciable transient voltage was produced.

The arc resistances just before a current zero were relatively high and comparable with the reactance of the transformer. These resistances were low enough to damp out the transient voltages except in the 5 amp region, where the first transient peaks were just greater than the 50 c/s peak.

(8.4) Capacitance Currents

When an 11 kV air-break circuit-breaker switched 3-phase insulated capacitor banks of 20, 60 and 180 μF per phase, the restrikes that did occur inside the chute were of a very minor nature and took place within a millisecond after current zero. No transient over-voltages were produced as a result of these restrikes.

The arcing times were between 4 and 8 loops, which allowed one phase to clear much earlier than the others. When this happened the voltage from one of the capacitor terminals to neutral rose to twice normal and the first phase to clear had to withstand three times the phase peak voltage.

(9) ARC-CHUTE SIZE

The size of chute required for a particular duty is determined from voltage/current characteristics, one of which is shown in Fig. 16. The characteristic can be altered by varying the chute parameters.

To force large current arcs above the cross-over, either the area of the slot or the driving force on the arc must be increased. To increase the area of the slot without prejudice to the magnetic circuit or the zigzag path, the slot must be lengthened, resulting in a taller chute. The alteration in the voltage/current characteristic is an increase in current for the same recovery voltage.

A change in the number of plates alters the characteristic mainly in the voltage scale. A small number of plates increases the driving force on the arc, because the runners are nearer together, and increases the recovery voltage per plate at the larger currents.

An increase in the width of the chute increases both the current and the voltage scales, but it mainly increases the voltage scale at the smaller currents.

Where the limit of performance has been determined by arcing over the top of the chute, increased performance has been obtained by increasing the cooler impedance or the height of the chute above the top of the slot.

The size of the chute also depends on the creepage distances and clearances adopted for the insulators and runners. As the circuit-breaker insulators are in an enclosure where free air circulation to the outside can occur, with possible contamination due to dust, creepage distances in excess of class A may be justified. Since the operation of air circuit-breakers depends upon the effective removal of ionized gases from the point of break, class A clearances may be used, unless impulse requirements dictate otherwise. At voltages above 6·6 kV the use of class A clearances across the gap results in more efficient circuit-breaker designs.

Typical arc-chute outside dimensions for 250 MVA at 3·3 kV are 17½ in long, 5½ in wide and 24 in high; the corresponding figures for 500 MVA at 11 kV are 27 in, 8 in and 28 in.

The chute of minimum dimensions is not always used for any given rating, since other factors such as panel size may be of overriding importance and fix one of the dimensions. These dimensional variations have not been found to affect the reliability of the arc chute.

Limit-of-performance curves predicted for chutes of different widths when checked by tests have been found to have negligible error. The consistency of performance has allowed chutes of different sizes to be designed not only for British ratings up to 500 MVA at 11 kV and American ratings up to 750 MVA at 15 kV, but also for voltages up to at least 33 kV.

(10) CONCLUSIONS

The research has shown that air-break circuit-breakers with insulated-steel-plate arc chutes are eminently suitable for high voltages. Meticulous attention to arc control has made the circuit-breakers very reliable, and their performance sets a new standard for air-break circuit-breakers in Great Britain.

The high degree of arc control is attributed mainly to the following factors:

(*a*) The driving field produced by the steel plates is available at arc initiation.

(*b*) The magnetic field acts, not only upon the portions of the arc that lie in the slots, but also upon the portions that lie parallel to the plane of the plates.

(*c*) High-speed photography has enabled a great deal of information to be obtained on the behaviour of arcs in the chute. In particular, it has led to the elimination of uncontrolled downstrikes which may be responsible for the inconsistent performance of some air-break circuit-breakers.

The chute construction is simple because there is no blow-out coil, and moulded mica-and-glass insulation has been found to be the best material for the plates.

Only class-A clearances or those determined by impulse requirements are needed across the circuit-breaker contacts, because the ionized gases are moved away from the point of break before the arc is extinguished.

Circuit-breakers with insulated-steel-plate arc chutes can be designed and built, not only for British ratings up to 250 MVA at 3·3 kV, up to 500 MVA at 6·6 kV and 11 kV, and for American ratings up to 750 MVA at 15 kV, but also for still higher voltages.

(11) ACKNOWLEDGMENTS

The authors are indebted to the directors of A. Reyrolle and Co., Ltd., for permission to publish the paper; to many colleagues for their contributions, and particularly to Mr. H. Leyburn and Mr. A. F. B. Young for their valuable advice and criticism.

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DISCUSSION ON THE ABOVE PAPER

Before the SUPPLY SECTION *25th February, the* SOUTH-EAST SCOTLAND SUB-CENTRE *at* EDINBURGH *3rd February, the* NORTH-EASTERN CENTRE *at* NEWCASTLE UPON TYNE *23rd February, and the* NORTH-WESTERN SUPPLY GROUP *at* MANCHESTER *14th April*, 1959.

Mr. C. H. Flurscheim (*at London*): Air can be used as an interrupting medium either at atmospheric or high pressure. When used at high pressure in air-blast circuit-breakers, short arc lengths of the order of ½ in for 60 kV are obtainable, because of the high electric strength and supersonic velocities of flow available. Such designs can therefore offer a performance closely approaching the ideal, i.e. interruption of short-circuit currents at the first current zero after contact separation combined with freedom from restrikes when clearing capacitive circuits. Because there is little leakage current and low arc resistance, over-voltage arising from current suppression when interrupting small inductive circuits requires external resistance damping, which can be readily applied. There is therefore a considerable performance incentive to develop compressed-air circuit interruption, which has resulted in very extensive use of high-voltage air-blast circuit-breakers.

When air is used for interruption at atmospheric pressure, very different conditions exist since air does not then possess high electric strength, and high-mass flow rates are not available. Interruption at voltages of the order of 11 kV is achieved by a process of lengthening the arc by means of magnetic fields and air flow of thermal origin. Arc lengths per volt of about 500 times those required in air-blast circuit-breakers are necessary. Resistance is introduced into the circuit by means of the arc itself, thereby effecting power-factor correction during the arcing period and reducing the effective circuit severity and the extent of the deionizing duty required from the multiple splitters in the arc chute.

There is considerable post-arc current leakage. This, together with the high arc resistance, tends to provide automatic limitation of over-voltages when interrupting small inductive currents, but leakage current is otherwise undesirable as it is one of the factors known to cause erratic interruption performance. The arc energy releases large amounts of hot gas with the consequential risk of gas flashover, particularly if there is an extra half-cycle of arcing at heavy current. The arc duration is likely to be long—

up to 12 half-cycles, as shown in the paper—and so the overall performance achieved is inferior to that available with modern oil circuit-breakers while the risk of failure is greater. The risk of insulation failure is also greater since there is more exposed non-ceramic insulation.

The incentive to develop h.v. air-break circuit-breakers operating at atmospheric pressure must therefore be sought outside the field of performance offered, and is undoubtedly centred on the fire-risk situation. Although the probability of an internal fire in h.v. air-break circuit-breakers is increased as compared with the modern metalclad oil circuit-breaker unit, there is no doubt that the consequences of a fire are reduced, and the risk of serious explosion, remote though it is with modern oil equipment, is eliminated. There is also some advantage with air-break designs associated with ease of maintenance of the contact system, especially where frequent operation is required.

There is therefore a case for the development of the 6·6/11 kV self-blast circuit-breaker, although the state of the performance now available may be considered comparable with the state of development of air-blast circuit-breakers in the 1930's. Much development work is still required to bring the high-voltage air-break circuit-breaker into line with the performance already obtainable from the best oil circuit-breakers, and the authors are to be congratulated on their contribution towards achieving this end.

Mr. J. A. F. Harvey (*at London*): The authors' explanation of the selection of interrupter type is too brief to do justice to their work, and their conclusions do not agree with our experience. Our philosophy is to use the bare-metal-plate type up to as high a voltage and MVA as is economic, because of simplicity, the inherent magnetic attraction for the arc and good thermal capacity. Whilst at 600 volts, the average chute-plate utilization is good, disproportionately more bare metal plates have to be provided as the voltage rises to ensure that the arc finds sufficient plates substantially simultaneously to interrupt. This is made more difficult by the increased strike-down clearance required to the moving arcing contact. These factors were probably responsible for the authors' experience at 6·6 kV with a bare-metal-plate interrupter. At 3·3 kV, however, the factors have been conveniently proportioned in a well-known design for 150 MVA.

For 150–250 MVA an insulating-plate arc chute gains rapidly on a steel-plate arc chute in terms of average voltage capability per plate when the voltage rises from 3 to 5 kV. When using insulating plates, the chute must have an extending labyrinth into which the arc is driven, and new arc cores form repeatedly when the dielectric recovery lower down in the plates or near the contacts is insufficient to withstand the arc voltage. The arc core location changes very rapidly. The change recorded over 1·25 millisec, shown in Fig. A, illustrates this.

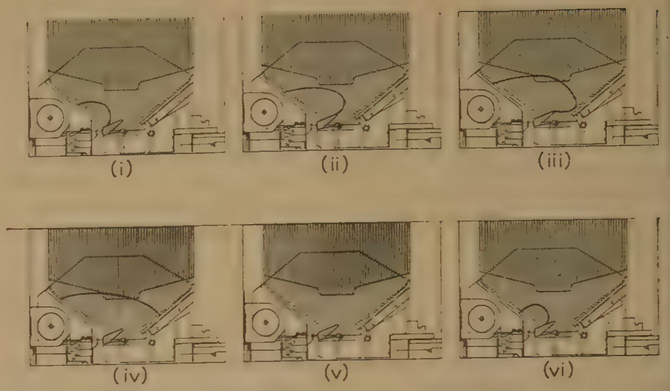

Fig. A.—Recorded arc movement in 6·6 kV air-break circuit-breaker.

Initial contact gap = ¾ in

	Time from parting of contacts millisec	*Instantaneous current* kA
(i)	3·25	1·02
(ii)	3·50	2·04
(iii)	3·75	3·14
(iv)	4·0	4·50
(v)	4·25	5·60
(vi)	4·50	6·80

The force on the arc is usually obtained from suitably placed magnetic material, and, in a particular labyrinth, its correct value depends on the increasing electric strength. Too much magnetic material induces excessive arc speeds and a high rate of formation of new arc cores, but magnetic material for the best high-current-arc speeds produces a weak field at lower values. We have added a series-coil field to provide a more even magnetic drive on the arc, and at short-circuit currents the coil excitation saturates and makes very little difference to the self field conditions. The current has to be transferred to the coil circuit during the early part of the interruption sequence. The general series coil requirement stated by the authors does not apply to the switching in, which can be done at various rates, but to the holding in after switching.

We have employed series-coil compensated magnetic drive for circuit-breakers working from 4 to 6·6 kV on which a dual-contact design is fitted providing advantageous circuit-making conditions. This is used to switch the coil mechanically when circuit breaking. The formation of new arc cores at controlled rate takes place whilst the contacts are moving the ¾–1½ in required to withstand the circuit recovery voltage.

Above 6·6 kV the period of formation of new arc cores persists for a longer time until the contacts open sufficiently, increasing the level of arc energy and unnecessarily destroying the performance of the arc chute. We have therefore approached the design by delaying the interrupting effort until the full arc voltage can appear without restriking. This requires the arc to be stored away from the contacts under low-energy conditions by initial magnetic control. At adequate contact gap, series coil excitation changes conditions to provide for interruption. The use of these two stages has yielded a high performance in a relatively small interrupter.

I am attracted by the freedom of action offered by magnetic manoeuvring using external magnetic material and would like to have the authors' views on this, since narrowing their chute at the bottom would appear to assist the prevention of down-strikes.

Mr. C. W. Mott (*at London*): The authors have been frank, and no doubt because of this, some of the information appears to be contradictory.

In Section 4.2 it is claimed that, contrary to the belief held by many engineers, welding occurs by melting rather than blow-off. Surely switchgear engineers acknowledge that melting, or at least the plastic stage of the metals, must be reached before contacts can weld. The contact blow-off phenomenon is something entirely different, and welding can take place with or without the blow-off effect being present.

In Section 4.2 and Fig. 5 the authors propound the advantages of butt contacts, and then in Section 4.3 state that it follows from Fig. 5 that multi-finger and blade-type main contacts should be used. The characteristics of the latter can be totally different from the butt type, and I have difficulty in following the authors' reasoning.

In Section 5.2 the authors give the reasons for connecting permanently the moving-contact side arc-runner to the moving contacts by a shunting strap. This has the disadvantage that the full service voltage is impressed across the chute with the circuit-

breaker in the open position, and leakage across a fouled chute could lead to breakdown. It is stated that, without the shunting strap, a low burning arc in one corner of the chute gave trouble. Could this corner of the chute be boxed in and the contacts brought to rest with an air-gap present between themselves and the chute? In this manner, voltage stress is removed from across the chute when the circuit-breaker is open.

A successful air circuit-breaker by itself is of little use to the electricity supply industry, and considerable ingenuity is required to incorporate it in a complete switchgear equipment without adversely affecting the performance of the chute. It is disappointing, therefore, to find that the paper does not include design and construction details of the unit shown in Fig. 1. The insulation of this is particularly interesting, and it will be noticed that some of the bushings are cranked—the first, I believe, to be used in any commercial switchgear unit.

Mr. M. P. Reece (*at London*): The arc chute described in the paper ingeniously combines the magnetic sucker plate, which has been used in certain types of oil circuit-breaker, and the ceramic chute, with very successful results. There is no doubt that, if it eliminates the cost of a blow-out structure without itself being too expensive, it represents a considerable step forward in the design of insulated chutes.

There are a number of specific points I would like to discuss. First, I think that the bare-metal-splitter-plate chute referred to in Reference 2 was one in which the arc was driven around a circular stack of metal plates by a radial magnetic field. This has somewhat different characteristics from the ordinary steel-splitter-plate type. It had much less post-zero current—so little that it was necessary to balance the capacitance of the plates to obtain equal voltage division during the restriking-voltage period—whereas the ordinary metal-splitter-plate chute has a post-zero current, at a few thousand amperes, of some tens of milliamperes, which serves to divide the restriking voltage equally between the plates.

With regard to contact tips mentioned in Section 5.1 of the paper, it is stated that thermionic emission from the tips affects the performance of the chute. This is difficult to understand, because, if a non-thermionic runner tip is used, there will be, at the most, a glow voltage of, say, 200 volts during the restriking-voltage period. Since post-zero currents in this type of chute are probably of many amperes, the glow would almost certainly change to a spot. Therefore, a thermionic tip might even absorb more voltage than a non-thermionic tip. In any case, the voltages involved would probably not be more than, say, 2% of the total voltage across the chute.

I assume that the arc cross-sections quoted in Section 6.1 were obtained photographically and include the glowing mantle around the arc core proper, because arc-current densities at atmospheric pressure are normally very much higher than the figures in the paper would suggest.

It is fairly well known that, when an arc is forced pneumatically or magnetically into a slot, there is a resisting force of a thermal nature, which, if the applied force is removed, will cause the arc to move out of the slot to a region where its losses are a minimum. By analogy with conservative systems, it might be assumed that the resisting force is proportional to the rate of change or loss per unit length with distance moved into the slot. That this is approximately true is a matter of everyday experience for arc-chute designers. Have the authors any quantitative information which would either support or refute this suggestion?

Mr. J. Solomon (*at London*): The authors are keeping in step with the dramatic growth in generator ratings since 1948. For example, the 3·3 kV 250 MVA circuit-breaker rating has recently been used for power stations with 120 MW sets. This is quite a big step forward from the 150 MVA 3·3 kV ratings previously available for this class of switchgear. Higher voltages are now necessary for the auxiliary systems, mainly because of the increase in size of unit transformers—about 20 MVA—and station transformers approaching double this rating. As oil-break gear was the only type available for 6·6 and 11 kV until recently, the authors' designs are of great interest to power-station designers. Current development seems to indicate that auxiliary switchgear will be required for 11 kV as well as 3·3 kV and 415 volts.

The authors refer to the inherent advantages of air-break circuit-breakers, but they might have enlarged on this in relation to oil-break switchgear. It does emerge that the air-break type incorporates the equivalent of resistance switching, which is an important point when considering the possibility of excessive transient over-voltages produced during switching operations.

With regard to the materials used for the arc chute, can they be described as non-hygroscopic and non-inflammable?

It is regretted that more details of the construction of the complete unit have not been given. For example, the authors have omitted to mention their use of cast resin for the main insulation of the fixed and moving portions of the unit, and also for the busbars and connections thereto. As the use of cast resin is quite a revolutionary change in design, it would be interesting to learn what led the authors to adopt it and also the service experience which has been obtained.

Mr. C. J. O. Garrard (*at London*): The main difficulty with arc chutes arises in getting them to work at low currents.

I recall some 11 kV circuit-breakers with arc chutes not dissimilar to those in the paper, in which the arc was blown into the chute by a powerful blast of compressed air.

We found on test that, with currents above a certain value, the air blast was superfluous. The performance improved as the current was increased. The circuit-breaker was designed for 350 MVA. However, it interrupted nearly 2½ times its nominal rating before failing through mechanical damage to the current-carrying parts.

The main objective in introducing air-blast circuit-breakers for higher voltages appears to be to reduce fire risk. However, experience seems to show that the risk of fire with air-break gear is not so much less than with oil circuit-breakers. I would not be surprised if the statistics were to show that, during recent years, the advantage has been with the latter.

In general reliability, there is unlikely to be much difference between the two types.

The remaining question is that of economy. It appears from the paper that, at voltages of 5–10 kV and above, air-break circuit-breakers are larger than the corresponding oil circuit-breakers. They contain more and more expensive material, and, on the whole, are more complicated.

If one takes into account the true cost of the circuit-breaker, the true cost of the building to house it, and the capitalized cost of maintenance, will the air-break circuit-breaker at voltages of the order of 10–20 kV be a more economic proposition than the oil circuit-breaker, and therefore a better engineering job?

Mr. W. F. C. Cooper (*at London*): I should like to comment on one aspect which has been referred to by several speakers, namely the question of fire and explosion, etc.

The most common failures on a circuit-breaker are not failure to clear its rated rupturing capacity. That does happen, but not often in a modern circuit-breaker. They are mechanical failures, such as fatigue stress, etc., in parts that have been used too often, and insulation failures. Mechanical failures also frequently lead to insulation failure. I have an open mind at present on the reliability of air-break circuit-breakers, but they do not explode and destroy the whole building when they fail.

Two common failures of oil-immersed switches at present are, first, isolating switches closed on faults, i.e. switches which

do not have a rated making capacity. This is outside the scope of the paper. The other is carbonized oil, which may be present from repeated operation of the circuit-breaker on starting a large motor or, more commonly, an arc furnace. This trouble was once very common, but it does not happen so often now.

More frequently, carbonization occurs on reclosing a public supply circuit-breaker several times during a thunderstorm, and quite a number of circuit-breakers blow up for this reason. Distribution engineers should not do this, but, in fact, it is done. I read a report recently of one circuit-breaker which had been reclosed five times. No oil circuit-breaker can be expected to reclose in safety five times on a line which is possibly faulty without the tank being removed and the oil and contacts examined and any necessary maintenance carried out.

What will happen to one of these air-break circuit-breakers? Will it be capable of reclosing five times or clearing five faults without attention? If it fails, is anybody going to be in danger? In the Annual Report on Electrical Accidents and Their Causes,* there is a photograph of several cubicle-type oil switches standing in the middle of a field. Five minutes before they were inside a brick building, but of this, nothing larger than a biscuit tin remains.

Mr. D. P. Sayers (*at London*): In the United States air-break switchgear is in general use for lower voltages, and oil-break switchgear is used mainly at higher voltages. In this country, the tendency has been the reverse, with oil used almost exclusively for voltages up to about 66 kV, and above that a fairly large proportion of air-blast switchgear. Could the authors offer some comment on why this position has arisen?

Mr. N. E. M. Cuthbertson (*at Edinburgh*): Although it is over 50 years since the first arc chute was developed, I think that it is only now, with the publication of the paper, that the full possibilities of this method of arc extinction will be fully appreciated. This particular type of switch is especially attractive, because of its inherent simplicity and probable cheapness of manufacture.

The qualitative efficiency of the device can be gauged if the speed of travel of the arc through the plates is compared with the rate of rise of a free arc in air (20–600 ft/s compared with 2 ft/s).

There are, however, two major drawbacks. The first is that the total arcing time for currents of about 100 amp is rather lengthy, and it seems a pity to have to introduce an air puff into a switch which would otherwise have the great advantage of being free from auxiliaries.

The second is that, whereas the formation of new arc cores at contact separation is not detrimental, the occurrence of such cores in the slots at the 'cross-over' point seems undesirable. I imagine that this is due to ionized gas remaining in the arc chute. Would a design where the plates are divergent towards the top of the chute not help to eliminate this trouble by tending to reduce the gas pressure near the contacts? Alternatively, could not some less-abrupt cross-over design be adopted, e.g. by having the plan view of Fig. 9 looking more sinusoidal.

I should like to challenge the statement in Section 8.2.3 concerning the generation of gas. Surely a larger quantity of gas is not, in fact, produced, but the turbulence caused by the moving contact tends to disperse the gas at it, while the gas produced at the fixed contact is not similarly affected and so accumulates there.

One feels instinctively that any attempt to dispense with the bulk and complexity of modern switchgear in general, and oil in particular, is to be encouraged. It can only be hoped that some further discovery of equal magnitude to the use of insulated steel plates will enable us to increase the maximum rating by one or two orders of magnitude.

Mr. J. A. Sullivan (*at Newcastle upon Tyne*): In order to assess the value of the type of circuit-breaker described in the paper it would be pertinent to compare its merits with that of the oil circuit-breaker which has been in use for many years.

The vast majority of major electrical failures of circuit-breakers which have occurred in this country over the last decade have been due to insulation faults. To improve on the performance of the oil circuit-breaker, the air circuit-breaker should provide a better insulation security. Unfortunately the air circuit-breaker has additional creepage paths to earth and between the poles because of arc chutes, and also additional creepage to earth in the form of the air-puffer arrangement.

Maintenance on the air circuit-breaker does not require oil-handling equipment, which is necessary for the oil circuit-breaker. However, owing to the complexity of contacts and the arc chute, it would appear that more time may be spent on the maintenance of air circuit-breakers than on the present oil circuit-breakers.

The fire risk is always levelled against the oil circuit-breaker, and it does exist. Experience of fires in this country, however, indicates that the risk is so negligible that it can be ignored. About three years ago a complete switchboard of oil-less circuit-breakers was destroyed by fire owing to insulation failure.

The air puffers are undesirable from the insulation viewpoint. Their omission would be preferable, particularly as they are only of use at low currents where contact erosion is negligible. A graphical comparison of the reduction of arcing using puffers would have been a useful addition to the paper. Do the authors consider that the puffers are really necessary, and have they considered the use of blow-out coils to reduce arcing at low currents in order to avoid the use of these puffers?

Mr. R. W. Blower (*at Manchester*): It is clear that the authors consider the air-break circuit-breaker has an important part to play in the future application of switchgear, but I notice that they make no mention of any advantages which they claim for it. In this country particularly, modern oil circuit-breakers have a background of service experience which gives them an excellent record of safety and reliability. It is difficult to see what outstanding advantage can be claimed for the high-voltage air-break circuit-breaker which can outweigh the confidence the user has in the circuit-breakers with which he is familiar.

It is interesting to see how the authors' work corroborates the results of investigations with which I have been associated, even though our work has only been on the bare-metal-plate arc chute which the authors seem to have abandoned to its fate from early on in their experiments. We have found that, at 3·3 kV at least, the problems outlined by the authors for this type of arc chute can be overcome, and a simple and efficient design for ratings up to 250 MVA can be attained.

In particular, we found, as did the authors, that the tips of the arc runners had to be protected to prevent erosion and the projection of copper vapour into the arc chute. We also found that copper arc runners gave the best results for the materials we tried, and it was also shown in our experiments that steep arc runners produce better results than more sharply divergent ones.

As the authors found, the biggest single enemy of arc-chute performance is ionization low down in the chute. In common with the authors we had recourse to high-speed photography, through Perspex-sided arc chutes, in order to solve this problem, and we found that one of our difficulties was the production of an adverse air circulation which carried ionized gases down at the ends of the chute and also left stagnant pockets at the junction between the arc runners and the extinguishing baffle.

This difficulty was overcome by altering the entry conditions at the bottom of the chute and allowing a freer entry of air, and also adding gas coolers so that the downflowing air at the ends

* Electrical Accidents and Their Causes (H.M. Stationery Office, 1956).

of the chute was deionized. The series arc between the moving contact and the arc runner was also a source of trouble. This was eliminated by a solid connection, which is exactly what the authors have done.

I was interested to note from Section 4.2 of the paper that the authors' experiments have borne out Holm's results on butt contacts and justified the criterion of 'melting voltage' for the short-time rating of contacts. As the resistance of a pair of contacts is not linearly dependent on the contact loading, it follows that subdivision of the contacts enables a smaller total loading to be employed without approaching the 'melting voltage'.

Could the authors state the criterion used in arriving at Fig. 5? Do the lines represent points where welding takes place?

The authors say nothing in the paper about the problems associated with closing high-voltage air-break circuit-breakers against heavy faults. Are very high closing speeds necessary in view of the pre-strike which must occur?

It is interesting to have the authors' vision of the future, with air-break circuit-breakers in service at 33 kV. I think it will be a long time, in this country at least, before the well tried and reliable oil circuit-breaker is superseded.

Mr. K. O. Goodwin (*at Manchester*): The authors' use of ultra-high-speed photography in studying arc behaviour is specially noteworthy. A team working on a similar project and using a magnetic method of tracing arc movement found very rapid movement of the arc branches, and the authors have undoubtedly added to this knowledge.

The embedding of magnetic material in the splitter plates would appear to be a difficult term of reference for the interruption of high voltage. In a free air-break circuit-breaker this requires much elongation and cooling of the arc, both of which are made easier by a sufficiently strong magnetic field such as can be provided by series-excited field coils. We have found that the arc can be interrupted with a lesser mass of material if it is forced by a high field into carefully designed passages. In addition, a high field acting on moving charged particles in the arc deflects them upwards and produces from their momentum a throughput of air which also helps in extinguishing the arc.

The authors' conclusions may be misleading unless qualified as follows:

(*a*) Some field at arc initiation is present in all magnetic air-break circuit-breakers owing to the arcing-contact loop exciting the iron circuit. This field can be adjusted by the tightness of magnetic linkage. Coil excitation superimposes on this an additional field at an opportune time.

(*b*) The provision of field over the whole length of the arc at the top of the slots is an achievement probably essential in the embedded-plate chute, since the field strengths given in Fig. 4 of the paper are well below those obtainable by series excitation.

From a practical point of view the separation of magnetic material and chute makes for easier handling of high-breaking-capacity chutes. A 15 kV chute of the authors' design is likely to weigh about $1\frac{1}{2}$ cwt, whereas a ceramic-plate chute for the same rating weighs about $\frac{3}{4}$ cwt after removing magnet parts each weighing less than $\frac{1}{2}$ cwt.

Mr. G. W. Davidson (*at Manchester*): The authors' remarks on contacts seem to indicate that, for a circuit-breaker having a short-circuit duty of 42 kA symmetrical, 16 contacts, or 8 pairs, are fitted as main contacts. If we assume that each contact is suitable for 100 amp, this would mean that the minimum size of circuit-breaker available for this rating is 1·6 kA. Are we to understand that this circuit-breaker would be installed for duties which require a full-load current of 100 amp?

It is stated that the arcing contacts are of the blow-off type. One would infer from this that, when the main contacts part, the current is transferred to the arcing contacts, which immediately blow, and a voltage is then impressed across the main contacts to cause more severe erosion than would occur if the arcing contacts were not of the blow-off type. I should have thought that, in a modern design, which this circuit-breaker unquestionably is, burning of the main contact would have received greater attention.

Mr. H. G. Bonson (*at Manchester*): In the power stations in the North West, Merseyside and North Wales Region of the C.E.G.B., there are some 750 existing switch units of 3·3 kV air-break switchgear of various makes, predominantly relying on the bare-metal-plate type of arc chute, but also including some with a blow-out coil and plates of insulating material.

Experience of the fault-clearing capabilities of the circuit-breakers has been good, and although there have been one or two instances of flashovers occurring in the various chambers of the switchgear when tripping to clear internal faults, there has been no evidence that such flashovers have been caused by failure of the circuit-breaker to clear. The good accessibility of air-break switchgear for maintenance has been achieved by some designs in which air-insulated conductors are situated a few inches apart in single chambers without phase segregation. Since station auxiliary systems are usually solidly earthed and have low-impedance fault-current paths, the occurrence of any fault to earth is accompanied by severe arcing and rapidly spreads to all three phases, causing considerable damage. Fig. 1 of the paper seems to indicate that the busbar and other conductors are largely encased in insulation, which should effectively remove this danger. Are there also barriers between switch units along the run of the busbar chamber? Furthermore, are any special ventilating arrangements made for the busbar and other chambers?

Most of the troubles which have been shown up by experience of air-break switchgear have been associated with mechanism failures such as the following:

(*a*) Failures to latch, owing to unsuitable material being used for latches and to wear of the mechanism.

(*b*) Dropping out several hours after closure, for reasons similar to (*a*).

(*c*) Failure to close, owing to defective closing contactor coils, open-circuited auxiliary and control-switch contacts, etc.

(*d*) Secondary wiring troubles caused by sharp edges of sheet-steel cubicles cutting into the insulation of the wiring.

Messrs. F. S. Fay, J. A. Thomas, D. Legg and **J. S. Morton** (*in reply*): Although, for some situations, air will always be preferred to oil and vice versa, the future of air-break circuit-breakers depends largely upon whether they can compete economically and technically with oil circuit-breakers. For general applications air-break switchgear with insulated steel-plate arc chutes is more economical than oil-break gear for the higher short-circuit and normal current ratings. The cost difference which exists at lower ratings, e.g. at 250 MVA, 11 kV, will decrease as air-break manufacturing techniques develop. At 33 kV air-break circuit-breakers cannot, as yet, compete with oil circuit-breakers.

There seems little difference in general performance between similarly rated air- and oil-break gears. The arc durations are shorter for air-break gear for all currents other than 50–800 amp, and, even here, there is evidence to suggest that times comparable with oil-break gear may be obtained. It has not been found that

post-arc conductivity leads to erratic performance. Technically, air-break circuit-breakers appear to have five main advantages:

(*a*) Less contact erosion, less insulation contamination due to short-circuits, and consequently a greater number of short-circuits before maintenance is necessary.
(*b*) Air-break circuit-breakers are very readily inspected and maintained.
(*c*) No oil-handling equipment is necessary.
(*d*) The fire risk is a minimum.
(*e*) The circuit-breakers are inherently non current-chopping and are ideal for capacitance switching or arc-furnace work.

The disadvantages are as follows:

(*a*) An increased insulation hazard due to the free movement of any atmospheric contamination through the cubicle.
(*b*) Owing to the insulation clearances required in air, on a current-rating basis, air-break-gear dimensions are greater than those for oil-break gear.

A consideration of these factors probably influenced development in the United States, particularly in the early days when the fire risk was a real hazard, with the results that 5–15 kV switchgear for indoor use in America is now largely air-break gear.

Butt contacts were used to obtain the experimental results shown in Fig. 5, the lines of which are drawn through points where the voltage drop is 90% of the melting voltage, but the abscissae are chosen so that the results also apply to all other contact types. The use of knife-blade contacts only increases the contact pressure when current is flowing. The reasoning of Section 4.3 depends on the fact that the short-circuit rating of a contact which has *n* equally-loaded contact areas is *n* times that of one of these areas.

In accordance with modern requirements, contacts are designed to carry normal current without deterioration even after they have broken short-circuit currents, and it is the latter which determine the contact size when normal current ratings are small and short-circuit currents are high.

Closing speeds are determined by the time from contact touch to fully close as well as by the pre-arcing time. Consequently, with either large contact overlaps or high voltages, the closing speeds have to be greater than normal.

The use of a shunting strap (Section 5.2) introduces a very minor reduction in insulation security compared with the hazard provided by a series arc formed low in the arc chute. Although the non-inflammable mica-and-glass insulation is very slightly hygroscopic, care has been taken to ensure that creepage paths are broken up by clean non-hygroscopic insulation.

Air puffers provide a cheap and reliable means of keeping the arc duration to a practical level at the critical current. Since the air-puffer tubes are made from Perspex and are separated from the contacts by a large air-gap, the additional insulation creepage-paths to earth may be discounted as a source of trouble.

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THE RELIABILITY AND LIFE OF IMPREGNATED-PAPER CAPACITORS

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SUMMARY

Reference is made to present trends in the encasing and hermetic sealing of paper capacitors. After a statement of the main primary causes of breakdown, the problems of impregnated-paper dielectric failure under d.c. and a.c. stress are discussed in the light of knowledge of various breakdown mechanisms gained principally during the last decade. Possible ways of prolonging capacitor life under d.c. stress are considered, and measures to eliminate early failures under both d.c. and a.c. stress are discussed. Achievement of very great reliability is considered a lesser problem with a.c. than with d.c. stress.

(1) INTRODUCTION

Despite the development in recent years of various possible alternatives, capacitors with impregnated-paper dielectrics are still widely used in d.c. and a.c. applications and influence the overall reliabilities of a vast range of equipment. Capacitor reliability is a relative quality since, for example, small capacitors with a mean life, L, used in a domestic radio receiver with a minimum useful life $L/2$, could be as reliable for their particular purpose as more costly capacitors with a mean life, $10L$, used in an important communication amplifier with a minimum useful life $5L$. In any specific group of paper capacitors mean life has an important influence on reliability because the nature of breakdown mechanisms results in a very great spread of lives.* Unless the ratio of mean capacitor life to minimum expected life of associated equipment is exceptionally high, a significant increase in reliability will result from an extension of mean life.

In a consideration of the ultimate reliability of components for use in submerged telephone repeaters[1] it has been claimed that capacitors (especially those subjected to high voltages) differ from other passive components in that, with life a function of time and severity of operating conditions, they 'wear out'. Thus, the possibility of indefinite extension of paper capacitor life is of practical interest in some applications, while any significant progress towards this goal must clearly provide valuable guidance in the design of all grades of capacitor. The paper reviews the principal phenomena influencing paper capacitor reliability under the two distinct conditions of direct and alternating voltage stress, and possibilities of extension of life are an essential part of the review.

(2) HERMETIC SEALING OF IMPREGNATED-PAPER CAPACITORS

The electrical properties of capacitor tissue and commonly-used impregnants such as petroleum jelly, mineral oil, chlorinated diphenyl and chlornaphthalene are impaired by ingress of moisture. Ineffectiveness of the seals on a paper-capacitor housing is therefore a possible cause of unreliability. With present designs it is, in fact, an uncommon cause of failure, but before considering the reliability of the dielectric itself, some reference may be made to present trends in the encasing and sealing of paper capacitors.

A detailed review of the development of terminal insulation design was made by P. R. Coursey in a paper[2] published in 1950. Except for the addition of sealing methods, which utilize the high adhesion to metals, low thermal expansion (of the same order as metals) and limited resilience of thermo-setting epoxy resins, it may be said that basic sealing methods used in the most reliable capacitors have not altered appreciably since 1950. To a large extent, Coursey's selection of two main groups, namely those with soldered vitreous insulation and resilient insulation materials, as the more efficient forms of sealing is still valid in 1959.

Since 1950, considerable progress has been made in setting standards for paper capacitors and British Standard specifications now cater for most fields of use, namely, d.c. use in telecommunication and electronic equipment,[3] power-frequency systems,[4] fluorescent-lighting control equipment[5] and the special requirements of radio interference suppression.[6] In the field of telecommunication it was originally common practice to specify different grades of capacitor for the same circuit function under temperate and tropical conditions. This practice is now uncommon, largely because a seal which is inadequate to prevent ingress of moisture under hot, humid conditions may well be unreliable under temperate conditions during the longer capacitor lives now expected. In B.S. 2131: 1956[3] the requirements for telecommunication and electronic equipment are covered by grouping capacitors, according to their ability to withstand extremes of temperature and humidity, into seven preferred (temperature category)–(humidity classification) combinations. Of these, the combination 25/70 H2 (−25° C to +70° C and Humidity Class H2 of B.S. 2011: 1954) is appropriate for many forms of telephone apparatus and reliable radio-communication equipment and it is here that resilient insulation materials find wide application. A very common housing for small- and medium-size capacitors is a seamless tubular aluminium container spun at one or both (open) ends on to an elastic washer with a Bakelite backing supported by a rill (indentation) in the tube. Internal connections are made to eyeletted tags, or plain eyelets supporting soldered wires, which press into the surface of the elastic material. This construction has been fully described and illustrated.[2] A useful extension of the method has been employed in capacitors of rectangular cross-section with rounded corners (Fig. 1). Methods of curling the open end of an aluminium can on to the elastic washer, in one press-operation, have been developed by various manufacturers. Typical performance of this class of seal in an accelerated damp heat test is illustrated by the results in Table 1. The samples tested were 1 μF capacitors, rated at 200 volts d.c. (working) 25/70 H2, housed in rectangular-section aluminium cases with rounded corners and with Bakelite-backed Neoprene top-seals. The shortest path between connector-tags over the

* From d.c. life-test results, Church[12] has given a typical ratio of 1 : 20 between shortest and longest lives in a distribution. With this ratio, a need for no failures under d.c. stress in the first 10 years appears to require a mean life of about 100 years.

This is an 'integrating' paper. Members are invited to submit papers in this category, giving the full perspective of the developments leading to the present practice in a particular part of one of the branches of electrical science.

Mr. Pitts is with The General Electric Co., Ltd. At the London meeting the paper was read on his behalf by Mr. C. E. Williams.

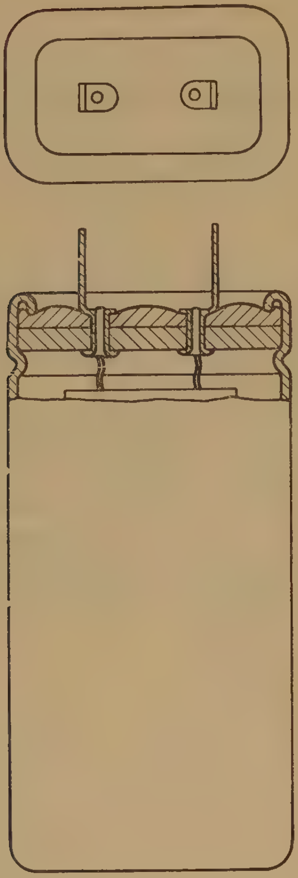

Fig. 1.—Capacitor in extruded aluminium case of rectangular cross-section with rounded corners, showing Bakelite-backed resilient seal.

external surface of the Neoprene was 10 mm and the shortest external path between either tag and case, 2 mm. With capacitors of small cross-section on which these paths are shorter than 2 mm, electrical behaviour of the elastic-material surface under hot, humid conditions becomes the main limitation of the construction. The use of radially-compressed resilient end-plugs[2] is necessary on the smallest capacitors. Successful operation with Neoprene seals between $-40°$ C and $+100°$ C has been reported[2] and polytetrafluorethylene has been used in more recent designs. With short surface-insulation paths on small capacitors, the requirements of the highest humidity classification, H1, are generally met by the use of soldered vitreous insulation. A construction using silvered ceramic washers with central holes for soldered connector-wires and soldered at the outer edges to a metal tube is well known.

Large paper capacitors for power systems which meet the requirements of B.S. 1650: 1955 are commonly housed in welded steel cases. With the smaller power-frequency capacitors which are now used so extensively in discharge-lighting control circuits, the trend in recent years has been to avoid the use of cases with soldered seams. Seamless extruded aluminium cases can be closed on elastic, Bakelite-backed washers, or, in some capacitors, the closure is an aluminium lid welded to the case by the argon arc process and elastic terminal bushings are used. In America, lighting capacitors are commonly housed in seamless drawn-steel cases with steel lids. A hermetic seal is obtained by rolling together the lid flange (previously coated with a sealing

Table 1

Insulation Resistance of Ten 1 μF Capacitors, rated 200 Volts D.C. (Working) H2 25/70, when tested in accordance with B.S. 2131: 1956 (Tests for Lot 'B')

No.	Position of measurement	Before test	After 7 damp heat cycles	After 14 damp heat cycles	After 28 damp heat cycles	After 24 hours' recovery
		MΩ	MΩ	MΩ	MΩ	MΩ
1	*a*	10 000	8 500	8 000	9 300	10 000
	b	59 000	53 000	44 000	35 000	37 000
2	*a*	6 900	6 200	5 500	7 400	7 900
	b	110 000	130 000	96 000	118 000	110 000
3	*a*	7 400	6 200	6 100	7 100	7 500
	b	130 000	80 000	43 000	42 000	45 000
4	*a*	7 200	8 500	9 200	10 000	10 000
	b	100 000	120 000	96 000	87 000	81 000
5	*a*	6 700	5 800	5 400	6 700	7 000
	b	130 000	180 000	83 000	87 000	87 000
6	*a*	6 100	5 100	5 300	6 500	6 500
	b	140 000	180 000	100 000	108 000	110 000
7	*a*	10 000	9 200	8 900	5 600	11 000
	b	180 000	130 000	100 000	93 000	110 000
8	*a*	7 000	6 100	6 100	7 200	7 200
	b	140 000	160 000	78 000	87 000	93 000
9	*a*	6 200	5 600	5 400	6 500	6 700
	b	140 000	160 000	96 000	65 000	65 000
10	*a*	9 500	8 300	8 000	8 400	8 400
	b	50 000	37 000	18 000	12 500	14 000

Insulation resistance in megohms measured at 500 volts d.c. for 1 min (corrected to 20° C).

(*a*) Measurement between tags.

(*b*) Measurement between tags (connected together) and metal case.

compound) and flanged open end of the case to form a tight double seam.* Lighting capacitors with metal lids, for operation up to 440 volts r.m.s., normally employ some form of elastic bushing either as a simple gasket or constrained within an extruded opening in the lid, frequently with both radial and axial compression of the elastic material. The latter is often a grade of silicone rubber which retains good elastic properties in the region of 60°–90° C and resists attack by chlorinated diphenyls.

Complete encapsulation of small tubular capacitors in insulation materials has been common practice for many years, and it has been difficult to obtain high reliability in the bonds between insulation material and wire terminations over wide temperature ranges and with high humidity. Hydrocarbon waxes are used in simple dipping processes, and capacitor windings can be injection-moulded in special synthetic thermoplastic waxes. Such simple processes cannot be used with thermosetting epoxy resins, but capacitors of temperature category $-40°$ to $+100°$ C and humidity classification H1 have been made with these materials.

(3) CAPACITOR LIFE AND DIELECTRIC BREAKDOWN

The development of more reliable paper capacitors is necessarily preceded by a fuller understanding of breakdown mechanisms in impregnated-paper dielectrics. In 1953, Garton and Church[7] reported various important developments in the investigation of such mechanisms, and much work in this field has continued at the British Electrical and Allied Industries Research Association. Despite the complexity of failure mechanisms in paper capacitors, considerable general guidance for the capacitor designer has emerged from researches during the last decade. The main primary causes of paper capacitor breakdown are summarized in Section 3.1.

* This is the type of seal used on light-gauge tinplate food cans. The material normally used to encase capacitors is a heavier gauge terne-plate (lead-coated steel).

(3.1) Primary Causes of Breakdown

Apart from gross mechanical faults which might possibly arise during the winding of a paper capacitor (e.g. damage to interleaving tissues, incorrect alignment of tissues and foils, misplacing of connecting tabs or severe creasing), the most important types of dielectric weakness which may initiate various failure mechanisms are conducting paths, ionizable impurities and voids.

(3.1.1) Conducting Paths.

These paths penetrate or are embedded in individual layers of tissue and originate either from air-borne particles reaching the tissue during its manufacture (the paper-mill rollers may be the source of some particles) or from similar particles introduced into the winding during capacitor manufacture. Microscopic and microelectric study[8] has provided strong evidence that the conducting paths are discrete carbonaceous particles (probably coke) whose diameters vary up to approximately $100\,\mu$. The upper limit of size depends upon tissue thickness when particles are introduced during paper manufacture owing to the calendering process. Up to the present, the exact nature of conducting paths has not been considered a significant factor when devising means to counteract their ill-effects.

Weak points or pin-holes in tissue may result from inclusion in the wound roll of abrasive, but not necessarily conducting, particles. This type of inclusion is particularly liable to cause trouble where the final geometrical shape of the capacitor requires the winding to be pressed flat during manufacture.

(3.1.2) Ionizable Impurities.

In this category must be included traces of inorganic salts capable of becoming free ionized acidic and basic radicals in the presence of moisture, any organic impurities which dissolve in the capacitor impregnant and become ionized (e.g. rosin in chlornaphthalene[9]) and any ionizable substances produced during deterioration of impregnant, tissue or other materials used internally in the construction of the capacitor.

(3.1.3) Voids.

The term 'void' refers to a tiny space in the dielectric containing atmospheric gases and possibly other gas liberated by chemical action in the impregnant and containing residual moisture if left after incomplete drying of tissue.*

(3.2) Dielectric Failure

Except under certain unusual conditions (e.g. localized dielectric contamination with highly dissociated materials) the short-circuit current following breakdown at a weak point in a paper capacitor destroys direct evidence of the cause of failure. Despite this difficulty, interpretation of life-distribution curves in the light of present basic knowledge of dielectric breakdown and with due regard to comparative conditions of test has provided convincing explanations of certain patterns of failure. Behaviour under the conditions of direct and alternating electric stress will be considered separately.

(3.2.1) Failure under D.C. Stress.

The results of life testing and research during the last decade have indicated that failure of paper capacitors under d.c. stress results from electrochemical deterioration within the dielectric, such deterioration being the primary cause of all breakdowns in the complete life distribution of any specific batch of samples. It is important to note that no statements of processing conditions and, in particular, of the extent of vacuum drying of tissue before impregnation, have been associated with the results of such tests. Having regard to normal industrial practice during this period, it is unlikely that many of the capacitors tested were vacuum-treated to the degree necessary for complete removal of free moisture. This factor must be taken into account when attempting to draw general conclusions regarding capacitor reliability under d.c. stress, since the presence of moisture favours most electrochemical processes.

By statistical analysis of considerable data Church[12] has shown that the observed wide variability of results of d.c. life tests can be explained by the presence in capacitor tissue of the dispersion of conducting particles of varying size. These particles must be responsible for tiny regions where stress is higher, to a varying degree, than the normal stress throughout most of the dielectric, and in such regions higher leakage current-density will accelerate electrochemical processes. With the chemical composition of the dielectric reasonably uniform (i.e. with no regions of gross contamination) the life of a capacitor will be determined by the highest stress, acting in one particular region.

From this picture of progressive deterioration towards inevitable ultimate failure—a wearing-out process—some direct relationship between applied electric stress and duration of life is to be expected, and an accelerated test should be an effective method of measuring reliability. From the results of widespread d.c. life tests over a number of years it has been found that the mean life of paper capacitors under such stress is inversely proportional to a power of the applied direct voltage which varies up to six with different capacitors.

Increase of temperature is another commonly-used mode of acceleration. In reporting d.c. life tests on capacitors impregnated with chlornaphthalene and mineral oil, Sauer, McLean and Egerton[13] pointed out that temperature acceleration is justified since the predominantly chemical and electrochemical nature of deterioration has been established and life is an exponential function of $1/T$ (T = absolute temperature). However, caution should be exercised in extrapolating experimental relationships to conditions where a change of state occurs in the dielectric. In earlier American investigations[17] with chlorinated-diphenyl-impregnated capacitors, Berberich and Friedman derived the relationship

$$L = A \times 10^{B/T}$$

where L = Life.
T = Absolute temperature.
A, B = Constants.

Different values of B for chlorinated diphenyl and chlornaphthalene have been obtained from the results of American[17] and English[20] work.

(3.2.2) Prolongation of Life under D.C. Stress.

The joint responsibility of conducting particles and electrochemical actions for capacitor failure under d.c. stress immediately suggests two broad lines of approach in attempts to increase reliability. Complete elimination of conducting particles, or a degree of process control in paper and capacitor manufacture, which reduced the maximum size of included particles to a figure substantially below the thickness of a single interleaving, would clearly prolong the mean life under normal direct-voltage and temperature conditions except where gross localized contamination of the dielectric caused early failure. In practice, there seems little chance of excluding particles completely in large-scale production, and, in any case, the wearing-out process would remain, although prolonged. The second and more practical line of approach is to accept the presence of conducting particles as inevitable and investigate the possi-

* German work[10, 11] indicated that complete removal of free moisture from capacitor windings was practicable with treatment at vacua of the order of 0·001 mm Hg. Use of vacua in the region of 0·1 mm Hg is still common in capacitor manufacture in Europe and America.

bilities of an indefinite extension of mean life despite their presence.

It is generally agreed that not all conducting particles included in capacitor tissue can be detected by the method described in B.S. 698: 1956;[14] only those particles with diameters approaching the thickness of the tissue are detected. The number of detectable particles (or paths) per square foot can now be maintained below 13 in 8μ tissue and below 8 in 12μ tissue of English manufacture. Hence, the chance of coincidence of the larger particles in adjacent tissues is remote, and the shortest insulated path between electrodes in a capacitor will be equal to or less than the total dielectric thickness minus the thickness of one interleaving, assuming that the presence of at least one particle penetrating the tissue is inevitable. Complete reliability would seem to depend upon the stress in this most highly-stressed region being insufficient to cause appreciable electrochemical reaction in a dielectric of high purity and great chemical stability. Before considering chemical aspects of the problem, it may be noted that nominal working stresses chosen for paper capacitors are considerably lower than intrinsic breakdown stresses[15] for similar insulation before the commencement of any long-term processes of deterioration. This may be illustrated by the results of short-time breakdown tests* on ten 2μF capacitors rated at 200 volts (d.c. working). (See Table 2.)

Table 2

SHORT-TIME BREAKDOWN TEST AT 24° C ON TEN PETROLEUM-JELLY-IMPREGNATED CAPACITORS RATED AT 2μF, 200 VOLTS (D.C. WORKING)

Sample	1	2	3	4	5	6	7	8	9	10
D.C. breakdown volts	1 750	1 750	2 200	2 000	2 100	1 400	1 900	2 000	2 100	1 400

These samples were wound with two dielectric interleavings of 9μ rag tissue, nominal density 1·2, and impregnated with petroleum jelly after vacuum treatment for a total period of 20 hours with a final vacuum of 0·2 to 0·5 mm Hg. Normal working stress in a region free of conducting particles is 11·1 volts/μ.

The mean breakdown voltage of these samples is 1 860 volts. If it is accepted that all breakdowns must have occurred in most highly stressed regions where the effective dielectric thickness between electrodes was not greater than 9μ, the actual breakdown stress must have exceeded 200 volts/μ—a figure of the right order to support the belief that intrinsic breakdown stress is approached, in the most stressed region, under such conditions of test.

In general, the results of short-time breakdown tests indicate that capacitors, if impregnated with a hypothetical substance which was completely pure and stable and in which no dissociation occurred either initially or after prolonged application of normal voltage stress at rated working temperatures, would have indefinitely long lives despite the presence of conducting particles. Complete elimination of all electrochemical actions would be a formidable problem, particularly since high permittivity (a valuable property of impregnants where small capacitor size and low cost are needed) is accompanied by greater ionization in solution. This has been born out by experience with two widely-used polar chlorinated impregnants, chlornaphthalene and chlorinated diphenyl. In some applications, reliability is so important that more space may be sacrificed to avoid using such an impregnant. The basic impregnant in many high-quality d.c. capacitors is a hydrocarbon—petroleum jelly or mineral oil—and the use of castor oil in capacitors for submerged transatlantic telephone repeaters has been reported.[1] In the latter case, American work indicated the greater stability of this material, compared with more common impregnants, at sea-bottom temperatures of the order of 5° C.

One possible solution to the problem of electrochemical deterioration is the use of additives which, without impairing the properties of an impregnant, will inhibit the ion-producing reactions or accept any products of such reactions which tend to shorten capacitor life. Investigation of 'stabilizers' has been the most popular approach during recent years. Much work by Egerton and McLean[16] and Berberich and Friedman[17] in America has been followed by extensive investigations[18, 19, 20] by Church and Garton in England, in which the deterioration of capacitors has been retarded by the preferential combination of active hydrogen, liberated at the cathode, with anthraquinone or azobenzene.

Two methods of increasing reliability in the sense of removing early failures, but without prolongation of life, may be mentioned. One suggestion[12] is the application of a short-duration high voltage to all capacitors, the intention being to kill the capacitors with the most highly-stressed weak spots by the type of failure mechanism occurring in short-time breakdown tests. It is hoped that, with short stress application, deterioration will be negligible in the surviving capacitors. By suitable choice of the 'sorting voltage' it might be possible to vary the percentage of killed capacitors to give an appropriate compromise between length of failure-free life and cost of broken-down capacitors, for any specific application. Two disadvantages of this scheme are the need for prolonged tests on many capacitors from any group, to establish that survivors are not damaged by the high voltage, and the destruction of a proportion of capacitors in any batch in order to achieve reliability. It may, however, be a more realistic approach than an attempt to eliminate electrochemical deterioration in small, cheap capacitors where a guaranteed life of a few years is desired.

A second method of removing early failures, which was adopted for American submerged-repeater capacitors,[1, 21] set out to break down any potential failures due to gross manufacturing defects. All capacitors were subjected to a pre-service life test for 4–6 months at $1\frac{1}{2}$ times operating voltage or higher stress. It is apparent that such a test will shorten the lives of all capacitors and can only be useful if life testing and statistical analysis have shown that normal capacitors will give a required life despite this general shortening.

In the light of present knowledge, there seems no basic reason why very great reliability should not be achieved with d.c. paper capacitors containing at least three interleaving tissues, manufactured under scrupulously clean conditions, processed under high vacuum to remove all free moisture and impregnated with a stable non-polar impregnant. However stable the impregnant, it is probably desirable to use a suitable additive to accept deleterious ions which could be produced after very slow chemical deterioration and/or electrochemical deterioration during prolonged service. Any future results of comparative tests performed on capacitors dried with different degrees of vacuum will be of great value and interest.

(3.2.3) Failure under A.C. Stress.

Although much knowledge has been gained regarding individual breakdown mechanisms and their causes, there is as yet no well-established general picture of a.c. paper capacitor failure in complete life distributions. During past years intermittent or persistent discharges in voids in the dielectric have been a predominant primary cause of failure in many a.c. capacitors, but with recent progress in methods of discharge-inception measurement,[22, 23] the capacitor designer can now ensure that

* A test in which the applied direct voltage is raised steadily to breakdown value in less than one minute.

capacitors are initially discharge-free at the highest voltages to be encountered in service. Such capacitors, if impregnated with a chemically-stable material after sufficient vacuum drying and de-gassing, seem, from preliminary results of extended tests, to offer the possibility of extremely long lives even under what are normally thought to be accelerated conditions of test. A lowering of discharge-inception stress during life has been commonly observed and in such cases failure due to internal discharges might still prove to be the cause of most breakdowns in the life distribution. With some impregnants the change of discharge-inception stress is slow. An example is provided by some particular tests where batches of pentachlorodiphenyl-impregnated capacitors are subjected to 1·5 times nominal working stress at 80° C and periodic measurements of discharge inception and extinction voltages are made, followed by a rest period of at least 4 days before stress is reapplied. In a typical batch of twelve 8 μF capacitors constructed with twin interleavings of 12 μ kraft tissue (density 1·2), a 5000 h test at 400 volts r.m.s. and 80° C produced no greater reduction of discharge inception voltage than 7% from a mean initial value of 1 200 volts r.m.s. In these capacitors the tissue contained traces of residual moisture before impregnation (the best vacuum during the drying and de-gassing process was 0·16 mm Hg*). A slower rate of fall of discharge inception voltage might occur in similar capacitors processed under high vacuum to remove all free moisture.

Other known mechanisms of failure which can occur with a.c. stress under certain conditions are thermal instability, chemical and electrochemical deterioration and short-time breakdown involving electronic bombardment in a weak spot, where, due to a gross winding fault or exceptionally large inclusion, stress is very high (about 15 to 25 times normal stress) when working voltage or a proof-test voltage is applied to the capacitor. The complete history of deterioration and failure at one weak spot in a capacitor can include periods in which different mechanisms operate in succession. For example, ionization in a void can produce local chemical deterioration leading to local thermal instability.

With the particular circuits commonly used for discharge lighting in England, a capacitor rated at 230–275 volts r.m.s. is frequently needed for direct shunt connection across the supply. In America, series connection with a higher capacitor voltage is more common. English practice has a certain disadvantage from the capacitor designer's point of view because two tissue-interleavings are inherently less reliable than three thinner interleavings, owing to conducting paths, but it is most uneconomic to use three interleavings in a 230–275 volt capacitor. Some users of this class of two-paper capacitor have experienced unusually high failure rates in individual installations, despite low average rates for the types of capacitor concerned. Capacitors in a single installation frequently come from the same manufacturing batch, and this trouble is thought to be due to exceptional contamination with materials causing rapid chemical or electrochemical deterioration in the dielectric. The writer has no direct experience of this trouble, but it has been investigated by the E.R.A. Such failures have been reported only with two-interleaving capacitors and not with those using three interleavings, even where nominal electric stress is the same in each case; hence, it may reasonably be inferred that conducting paths are a contributory cause of failure. A useful test has been described[24] to reveal ionic impurities in materials, such as packing pieces, used in capacitor construction. The material is extracted with highly-purified trichlorethylene and a conductivity measurement is made in a special cell.

* Total dynamic pressure measured with a Pirani gauge during pumping.

Some forms of gross contamination in capacitors can be revealed by change of power factor after the capacitor has been aged at elevated temperature, say 85° C, for about 1 000 h but with no stress application,* and the test is most sensitive when power factor is measured at elevated temperature and about 20% rated voltage. The ageing period allows serious ionic contamination to diffuse into the dielectric and produce significant change of power factor. Loss under alternating stress in an impregnated paper-capacitor dielectric, with its thin films of impregnant contained in the tiny pores of the tissue, results mainly from the oscillation of free ions in the impregnant. It has been observed that in some capacitors tan δ varies appreciably with change of applied voltage at high ambient temperatures and reaches a maximum when a voltage in the region of 0·1–0·2 of the normal working voltage is applied. Garton has explained[25] that this variation occurs because the pores in capacitor tissue are comparable in size with the amplitudes of oscillation of ions and the cellulose walls can limit the motion of ions to less than their free amplitude in the liquid impregnant in bulk.

At some future date the life distributions of representative mineral-oil-impregnated capacitors of English manufacture will be known from the results of current E.R.A. tests[26] at normal working stress and at approximately 75% discharge-inception stress. In the past, little information regarding the lives of power-factor-improvement capacitors has been published. English work on chlorinated-diphenyl-impregnated capacitors cannot yet yield any full information regarding life because manufacture of these capacitors commenced within the last eight years. American designers have the experience of more than 20 years' use of this impregnant.

(3.2.4) Increased Reliability Under A.C. Stress.

At present there is some difficulty in considering the possible prolongation of paper capacitor life under a.c. stress because, with capacitors using the more recent and increasingly popular chlorinated diphenyls,[27] insufficient time has elapsed for the completion of whole life distributions, even in America.† It seems that average lives of capacitors of present-day manufacture designed to operate well below discharge inception may be adequate for most uses at power frequencies. The main problem, then, is the elimination of early failures, and with alternating voltage, any failure in 10 years might well be considered 'early'.

A primary aim in a.c. capacitor design is the avoidance of internal discharges at any time during the required life of the capacitor. Thus, any chemical or electrochemical effects producing a lowering of discharge-inception stress during capacitor life are important factors in the comparative behaviour of impregnants. In some power-capacitor applications it may not be practicable and economic to ensure that discharge-inception stress is never exceeded for short periods in service. In such cases ability to recover is an important property of an impregnant. This property is under investigation with chlorinated diphenyls and mineral oils, and prominent workers[28] in England, Italy and France have concluded that a capacitor dielectric will 'forget' the effects of ionization provided they have not been too severe, but, if any chemical deterioration results from discharges, complete recovery is impossible.

An important recent research problem is the mechanism of discharge inception with increasing stress in impregnated-paper dielectrics which are void-free at normal operating temperatures and stresses. When the voltage applied to an oil-impregnated

* This test has been devised by Garton and Church of the E.R.A.

† A particular American manufacturer testing very early samples of pentachlorodiphenyl-impregnated capacitors has reported survivals after 26 years' stress application.

capacitor is raised to a certain value, a gas bubble is formed in the dielectric in which discharges occur. Some work to investigate this bubble formation under stress has been reported,[29] and the presence of moisture in the dielectric appears necessary for gas evolution. Further investigation of the extent to which discharge-inception stress can be raised by greater drying of capacitor tissue, up to the point of complete removal of free moisture before impregnation, will be of obvious value.

Application of a short-duration high voltage to eliminate potential early failures is a possible measure to increase reliability of a.c. as well as d.c. capacitors (see Section 3.2.2). Where, however, exceptional contamination with ionizable materials is the primary cause of early failures under a.c. stress and such contamination is localized, some potential early failures may well survive a high-voltage test designed to produce short-time electronic breakdown in regions most highly stressed owing to conducting particles.

An important difference in the observed behaviour of paper capacitors under d.c. and a.c. stress is that, while electrochemical actions occur to a significant degree under d.c. conditions (certainly, in the majority of capacitors produced up to the present time), there is evidence that under a.c. stress electrochemical actions may be insignificant in capacitors with well-dried tissue and uncontaminated stable impregnants.[30] Thus, an extended pre-service test offers the possibility of eliminating potential early failures due to exceptional contamination of the dielectric, without significantly shortening the lives of survivors. Where lighting capacitors are made in large quantities, a test of this nature would require much space and equipment. The cost of the latter might be offset to a certain extent by the large power-factor improvement output available from the capacitors under test. If, for example, 5 000 8 μF 250 volt units were manufactured each week and all were subjected to a 30 week pre-service test at 400 volts r.m.s., a reactive output of 60 400 kVAr would be available. Many geographical and engineering problems would be involved in utilizing this output. Even with capacitors employing two interleaving tissues the problem of early failures may well be solved by better material controls, such as the test for ionic impurities mentioned in Section 3.2.3[24] and by further improvement in processing conditions.

(4) THE FUTURE OF IMPREGNATED-PAPER CAPACITORS

The paper capacitor is a component of long standing, but some of the most recent discoveries in the fundamental science of dielectric breakdown have a direct bearing upon its reliability. Consistent reliability is achieved only with the greatest care and cleanliness in manufacture, together with exacting and comprehensive raw material tests. In this connection it is interesting to note that with, for example, a single 20 μF winding for power-factor correction, the total area of a 24 μ-thick dielectric is about 110 ft^2, despite use of a polar impregnant of high permittivity. One weak spot in this vast area can be responsible for failure of the capacitor.

There seems a possibility of significant increase of reliability with more elaborate vacuum treatment of capacitors before impregnation, but it has yet to be established whether complete removal of free moisture is necessary to achieve the lives and reliability desired in practice.

At present the achievement of greater reliability appears an easier task with capacitors for use at power frequencies, and, in this field, no successor to the paper capacitor seems likely for many years to come. An impregnated-paper dielectric has well-known inherent limitations in respect of stability, losses at higher frequencies and relative bulk, which limit its application in communication circuits, but many uses still exist where the advantage of low cost is already accompanied by considerable reliability. Improvement in the latter respect is mainly a chemical problem.

So many factors can influence the reliability of paper capacitors, and the application of similar methods in different manufacturing plants can produce such varying results, that maximum interchange of information is invaluable. Much research and development is performed on a national basis in England, and with capacitors for power systems the value of international liaison in investigating fundamental problems has been shown by recent joint work planned by the C.I.G.R.É. Capacitor Study Committee. Similar liaison on fundamental problems of d.c. capacitors would be most beneficial.

(5) ACKNOWLEDGMENT

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DISCUSSION BEFORE THE INSTITUTION, 5TH MARCH, 1959

Mr. C. G. Garton: A pre-service life test for eliminating early failures is popular in America, and was applied to the capacitors in the transatlantic telephone cable. There are, however, two kinds of early failure. One arises from a gross defect, such as a misplaced piece of foil or a large conducting particle; this will no doubt be found by a life test, but may equally well be found by a suitable proof test. The second arises from samples in the tail of the distribution of normal lives, which is mentioned in the paper as covering a 20 : 1 spread. This distribution is continuous, and if the shorter lives (other than those due to gross defects) are removed by any process, the remainder of the distribution is brought correspondingly nearer to failure. I am therefore not convinced of the value of a pre-service life test.

Regarding the author's challenge that there is at present no effective competitor with impregnated-paper capacitors, I am not sure that we should ignore the low-loss plastic film as an alternative. Admittedly a dielectric such as impregnated polystyrene foil has disadvantages—cost, low permittivity, and with smooth films, a difficulty in impregnation—but it also has large potential advantages: the very low energy loss means that thermal stability and cooling can be ignored; impregnation can be facilitated by use of roughened film, and some preliminary experiments made by the E.R.A. indicate that the discharge-inception and recovery characteristics may be better than those of paper, partly because of the ease with which water is removed. For some unexplained reason, recovery from discharges caused by a surge is more rapid with polystyrene than with paper. I therefore regard the low-loss plastic film as a possible serious competitor to paper, although the latter is an excellent dielectric.

My last critical point concerns the comparison of alternating and direct current with respect to electrochemical action. Admittedly this action is less rapid with alternating current, but its existence has hitherto been obscured by the importance of discharges with a.c. Now that capacitors are usually free of discharges, electrochemical effects are becoming more evident. For many reactions, a half-cycle at 50 c/s is a long period, and the electrolysis is not reversible, as may easily be shown by passing an alternating current between platinum electrodes in a weak acid. In service on a.c. systems many capacitor failures occur, especially with the smaller and cheaper types, which are certainly electrochemical in origin.

Extending the idea contained in the phrase 'wearing out of capacitors', I suggest that all insulation 'wears out' from the time a voltage is applied to it, for the one reason, if for no other, that all insulation has some ionic conductivity. Since this necessarily implies a transport of matter to the electrodes, the insulation is slowly decomposed and converted into other substances. It may not have been sufficiently emphasized that research on capacitors in fact applies to all insulation, since any piece of insulating material with electrodes forms a capacitor of some kind. The mechanisms of breakdown are quite general, whether they occur in a capacitor or a turbo-generator.

I can add a little to what is said in the paper on the life tests on model power capacitors which have been in progress at the E.R.A. for the past three years. The evidence to date, for the majority of the samples, is that they can be run for at least 12 000 hours at 75% of their discharge inception voltage without a measurable fall in that property. In one group of samples this implies running at three times their rated voltage. To obtain such results, the supply must be free from surges and there must be no large reduction of gas pressure within the cases. Early breakdowns have been experienced when these conditions have not been met.

Finally there is a need for more investigation of conducting particles. It is usually assumed that the importance of these lies in the few which are large enough to penetrate, or almost penetrate, a complete sheet of paper. There is a good deal of evidence that paper in fact contains a very much larger number of extremely minute conducting particles, and that these are responsible for the continuous and wide distribution of lives. Proof of this hypothesis would be a useful step forward.

Mr. T. R. Scott: The most contentious part of the paper appears to be the Introduction, where the author suggests that a capacitor with a mean life of L and a minimum useful life $L/2$ can be as reliable for its purpose as a more costly capacitor with a mean life $10L$ and a minimum useful life $5L$.

There are very important differences between the two types of capacitor. The manufacturer of the high-quality type, knowing his materials, his plant and his processes and taking into account the recent discoveries on causes of breakdown, does his best to produce capacitors of almost infinite life. If he is successful he can afford to weed out the weak ones by fairly drastic tests, such as 4–6 months at $1\frac{1}{2}$ times operating voltage. The minimum life of the sound ones is relatively unaffected.

The weak ones are weak because of human errors in manufacture. When the minimum life of the capacitor falls to a low value (e.g. $L/2$) so that the weak units are relatively indistinguishable from the early failures, we reach a situation which can be very awkward if the capacitors are employed in modern complex electronic systems. Early failures of components in such systems cause excessive trouble and are very costly. Being of the integrating type, the paper might well have dealt more fully with this aspect.

Mr. P. R. Coursey: The economic factor affecting reliability of capacitor performance has been hardly mentioned. The expected life of a capacitor dielectric is a function of the stress applied to it. A quantitative relationship connecting life and dielectric stress is not so well known for a.c. capacitors as for d.c. ones. However, a lowering of the working stress by, say, 20% may easily give more than 100% gain in the expectation of life for a cost increase of perhaps 40%. In many instances, therefore, it may be cheaper in the long run to spend more initially than to waste material in subsequent breakdowns and drastic efforts to eliminate the tail of the life-distribution curve that contains all the 'sports', quite apart from the cost of replacing any failures.

How does the author judge 'complete removal of moisture' from the capacitor paper? The measurement of residual moisture is not easy, and is virtually impracticable on a complete capacitor. It appears to me that in all cases we have two opposing processes to consider—the degradation of the cellulose by the heat for drying, and the moisture removal by the heat and vacuum. The former will always release some moisture, otherwise bound and harmless. The value of the extremes of vacuum suggested would seem to lie mainly in more speedy removal of the moisture so that less destruction can occur. On the other hand, too rapid removal may leave some moisture trapped in the interior parts which will subsequently ruin the reliability of the capacitor.

The pre-service life test, provided that it is only a short one, has some attractions for small a.c. capacitors (such as are used with fluorescent lamps) as a possible means of eliminating some of the potentially weak specimens inevitably associated with capacitors having only two interleaving papers. Can the author recommend any alternative reliable production test method?

Mr. R. M. Barnard: It would have been better if the title of the paper had referred to capacitors using foil electrodes, since the paper should not suggest that the mechanisms described would apply completely to capacitors using metallized electrodes.

There is only a brief reference to the H1 component, which is essential for extreme reliability in communication equipment. On the submerged-repeater capacitors referred to, rubber bungs were not used to insulate the terminations.

The ten results in Table 2 suggest an approximation to a Gaussian distribution, the extent of which is demonstrated in Fig. A, which shows the effect of the area of dielectric employed on the average breakdown voltage, and the increase in deviation from a Gaussian distribution with increase in area. The curves were taken for capacitors using three layers of paper and show that as the area increases first one and then two layers become ineffective.

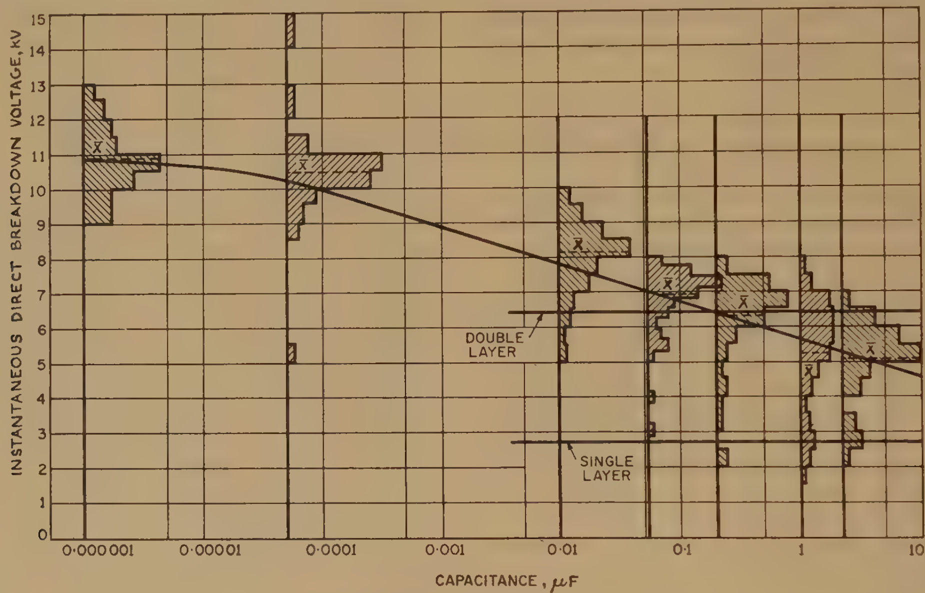

Fig. A.—Instantaneous voltage breakdown histograms as a function of capacitance.
3 layers, 8-micron rag tissue.

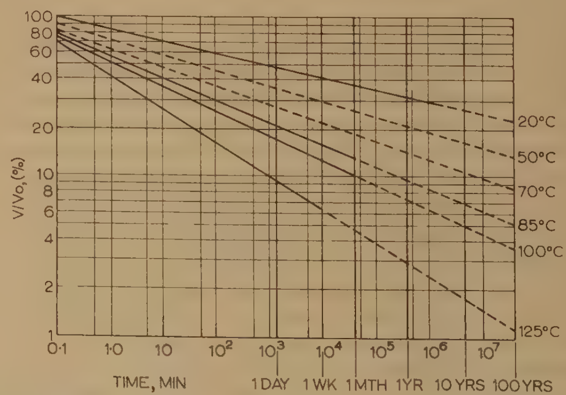

Fig. B.—Direct-voltage/time characteristic, oil-impregnated rag-base tissue.
V = Test voltage at test temperature.
V_0 = Instantaneous voltage taken at 20° C.

Fig. B shows the 'life' of a capacitor in terms of various test voltages expressed as a percentage of the voltage for instan-

taneous breakdown. In conjunction with Fig. A and other information it can be applied to any capacitance and any dielectric thickness, and enables an estimate to be made of the time taken for the first failure in 100 capacitors to occur. The curves emphasize the extreme dependence of working life on operating temperature, and with other information it can be deduced that for a 2 μF, 250-volt working capacitor the present temperature ratings are such that 1% of the capacitors would fail in 1 000 hours working. This life is probably very much shorter than most users imagine, and the latest British Standards for capacitors, e.g. B.S. 2131, draw attention to this point.

Mr. A. C. Lynch: Any judgment of reliability will be framed with a particular application in mind and will be influenced by the cost of replacement if a capacitor fails (which is not merely the cost of the capacitor). When this is very high, the failure rate must be kept so low that it is difficult to measure, and there is no certainty that the quoted range of 20 : 1 between maximum and minimum lives in a batch applies in such a case. In these conditions the mean life of the batch is of no interest; we need to know the likely period before the first failure. The relation between these two quantities is, regrettably, unknown.

Mr. E. C. Lee: The breakdown values for some d.c. capacitors quoted in Table 2 are rather low, as is also the d.c. working stress, which is about that used for a.c. working on r.m.s. values.

My experience indicates that, for a.c. capacitors, drying times of about 72 h with final pressures not exceeding 0·01 mm Hg are necessary to ensure uniformity of quality, and good drying would seem even more important for d.c. capacitors.

In his reference to discharge tests the author does not state the temperature at which discharge was measured; nor does he give the discharge extinction values, which may be of greater importance than the inception value.

One selective test to eliminate early failures is to apply an alternating voltage to elements following a preliminary vacuum drying period. By a suitable choice of voltage this test can be made very effective, as evidenced by the very low proportion of rejects during final test, with the additional advantage of avoiding the processing of potential reject elements.

There is little reference to the effect of pressure on the life of a.c. capacitors. In comparative testing it is important to determine the pressure within the element case, for an increase of even 10 in Hg above atmospheric gives a life 50% greater than similar elements held at atmospheric pressure. This effect seems more pronounced with low-viscosity impregnants, and for this and other reasons a high-viscosity impregnant appears to offer many advantages, such as higher permissible working stress, higher ionization-inception voltage and greater chemical stability. When, for thermal reasons, a low-viscosity impregnant must be used, the degasification should be thorough and contact with air prevented by completely filling the capacitor tank and providing some form of sealed conservator to accommodate expansion and to ensure a positive pressure.

Mr. W. A. Stickley: The author mentions capacitor seals but makes no mention of their success or failure. It is our experience that leakage of impregnant is too common at present, and more work should be done on terminations of seals.

In Section 3.2.4 the author mentions failure before 10 years which might be considered 'early'. It is our experience that properly used oil or petroleum-jelly capacitors can be expected to give considerably more than 10 years' life. Are there any published data which would support the theory that the chlorinated-diphenyl capacitor would have a similar or longer life than a petroleum-jelly or oil capacitor?

It has been suggested that a thicker dielectric or more papers would improve the capacitor. All a user can do is to read what is on the box. What is inside it is entirely the responsibility of the manufacturer, who should use the correct dielectric.

Mr. H. F. Church: I was surprised that the author made no mention of the quality of the paper. It is well known that with chlorinated impregnants, and especially under d.c. stress, it is essential to use kraft rather than rag paper. This is an indication that the type of cellulose used, and perhaps the nature of non-cellulose constituents, is important. Many years ago the E.R.A. showed the importance of cation exchange in cellulose. For the best electrical properties and long life, paper should be treated with a salt solution containing the right type of cation. It is interesting that, 15 years after those experiments, Russian workers are attempting to confirm the results.

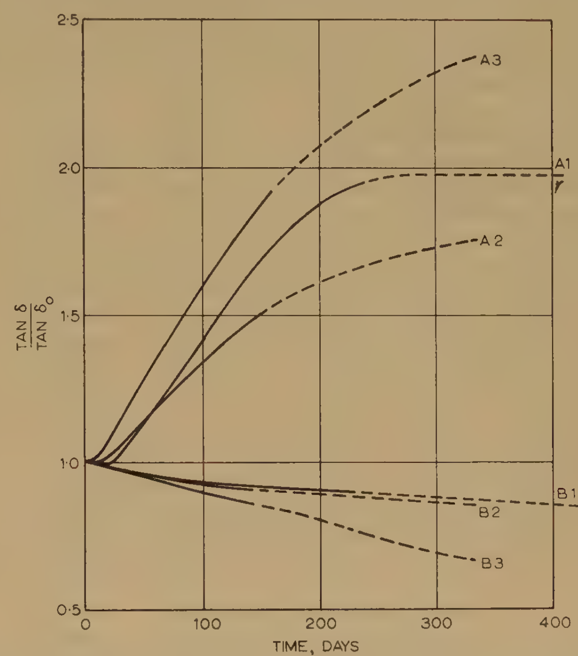

Fig. C.—Variation of tan δ of chlordiphenyl capacitors with time at elevated temperature.

——— Capacitors kept at 63° C.
— — — Capacitors kept at 85° C.
tan δ measured at 100 volts r.m.s. and 63° C.

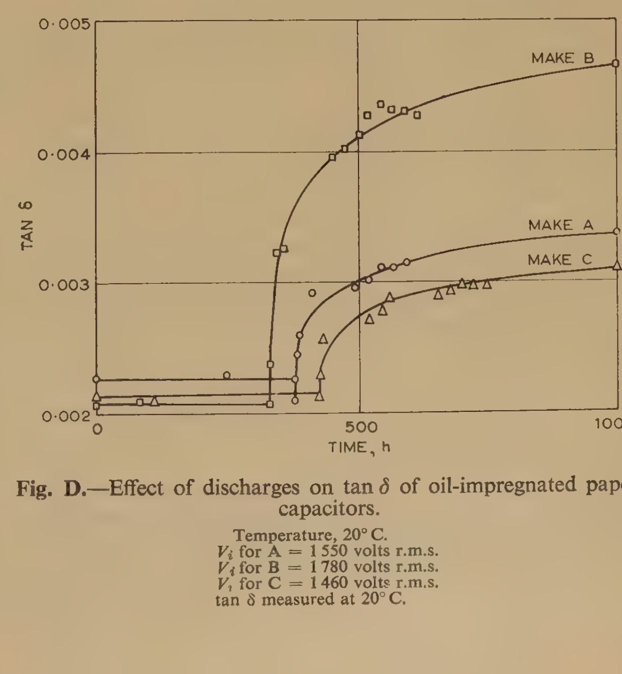

Fig. D.—Effect of discharges on tan δ of oil-impregnated paper capacitors.

Temperature, 20° C.
V_i for A = 1 550 volts r.m.s.
V_i for B = 1 780 volts r.m.s.
V_i for C = 1 460 volts r.m.s.
tan δ measured at 20° C.

Has the author any experience of migration of silver across silvered-ceramic bushings, and, with vitreous terminals, have corrosion troubles been experienced, and if so, under what conditions?

In amplification of the author's remarks about ionizable impurities, Fig. C shows the change of power factor in two groups of capacitors with chlordiphenyl impregnant. Group A included a piece of cellulose sheet material containing harmful impurities, while in group B that sheet material was omitted. Losses have increased greatly as a result of the impurities, but the effects are not noticeable initially. Considerable time is necessary for diffusion of the impurities into the unit.

Harmful impurities can also be formed in a capacitor by the action of discharges, even if they take place for only a relatively short time. Fig. D illustrates this for three different makes of capacitor. Discharges took place at the discharge-inception stress V_i for 15 min in each case. It is observed that loss angle increased considerably after cessation of the discharges on removal of the voltage.

Mr. E. T. Norris: Emphasis has been laid on the life for the first failure as distinct from the mean failure. This emphasis, in fact, applies not only to condensers but to all electrical machinery, transformers, cables, generators, etc. Surely the only way to get at this first failure as a prophecy is from the statistical distribution? It has been tacitly assumed that these statistical distributions are Gaussian. But if the failure is due to particles and is of a weak-link nature—which seems to be the general assumption—the distribution may not be Gaussian. In recent years there has been much study and development of various new extreme-value distributions to meet this sort of condition.

Broadly, if manufacture is on a mass-production scale and under conditions of quality control (i.e. consistent errors have been eliminated), the output will follow a statistical distribution, but not necessarily one which can be explained mathematically. Once this statistical distribution is established, the nearest approach can be made to the determination of earliest failures.

Mr. F. Moores: Unless the processing of capacitors is thorough and uniformly effective, it is difficult to make a comparison of the materials used. Processing may be considered to commence with the winding operation, because it is essential to ensure that nothing deleterious, such as dust and grit, is allowed to enter.

The effectiveness of vacuum drying can vary with the width of the tissue, for it is more difficult thoroughly to dry a capacitor element wound with 8 in wide tissue than one with 4 in tissue. For some types, the wound elements are packed into the final casing before the drying is carried out, and the lid may also be fitted, a hole being left through which the drying is done. This makes the drying difficult and it may be impossible to obtain within the container the final low absolute pressure necessary to minimize the moisture content.

The use of the latest high-speed vacuum pumps does not necessarily reduce the overall drying time appreciably, because the tissue contains 5–8 % of moisture by weight, and the majority of this must be removed by the roughing pump before the high-speed high-vacuum booster pump can be brought into operation, when a very high final vacuum is obtained and it is possible to obtain an absolute pressure corresponding to the vapour pressure of the tissue itself.

In a recent paper* on gas-pressure oil-impregnated cables, it was stated that the moisture content remaining in the pre-impregnated paper after impregnation was approximately 2000 parts in 10^6, which is approximately a wine-glassful of moisture in a cubic foot of the impregnated paper, and this is considered alarmingly high by capacitor manufacturers. Furthermore, it was stated that, during the lapping and before final sheathing, a further 2000 parts in 10^6 may re-enter the paper; yet a reliable cable is produced. With the high-speed high-vacuum pumping equipment we find that the residual moisture in the dielectric is reduced to approximately 200 parts in 10^6.

From my experience of making capacitors in a factory where the winding operations are carried out in an air-conditioned room, and the drying carried out to the lowest possible absolute pressure, much higher insulation resistances are obtained, and there is also a considerable reduction in the number of rejects during manufacture.

Mr. D. F. Chapman (*communicated*): Every effort should be made to put the results of much recent research work on dielectrics into practical use in the manufacture of capacitors. In particular, such research work has emphasized the importance of careful control of both materials and processing to eliminate impurities. Manufacture of still more reliable capacitors depends very much upon the care which is taken to exclude these harmful impurities. Every effort should also be made to find satisfactory tests which can be applied to capacitors to detect the presence of contamination by impurities. These tests should then be incorporated in the appropriate British Standard.

It is suggested that, for some types of capacitor used in fluorescent-lighting circuits, some form of over-voltage and over-temperature accelerated life test should be made mandatory on a proportion of capacitors from each manufacturing batch. Such a test would reveal faults in processing and electrochemical deterioration due to contamination.

I believe that the capacitance of capacitors increases slightly during life. Is this in any way due to deterioration of the dielectric?

Mr. R. D. Jones (*communicated*): Apart from the reference to the conducting particles in paper, the author says very little about the basic element of the paper capacitor. The importance of eliminating, or at least minimizing, ionic impurities in the dielectric was stressed, but again there was no hint of the contribution made by the paper. An attempt to control the amount of such impurities is made in B.S. 698: 1956 by the tests for conductivity of aqueous extract and pH-value.

In work carried out in my company on material from various suppliers (of British, Finnish, French, German and American origin), various batches from some suppliers and using both rag and kraft types, considerable variations in the life-test performance have been found.

The life-test results and B.S. 698 tests are not very clearly related. This does not mean that the tests are of no value, for clearly they do help to achieve a certain standard. However, one begins to consider what can be done to find a quicker way of selecting the best material without having to carry out a lengthy life test. I suggest as a first step the possibility of a conductivity test on an extract of the paper in petroleum jelly, mineral oil, chlorinated diphenyl or whatever other impregnant one proposes to use. Alternatively, to find some more suitable solvent than water, possibly the use of trichlorethylene referred to in E.R.A. Report L/T375, would be more suitable in a raw-material specification test for paper.

Insulance tests are a valuable guide to paper-capacitor reliability; good-quality kraft tissue gave much higher values of insulance than rag tissue when processed as capacitors under identical conditions in petroleum jelly, and the same samples also had better life characteristics on accelerated d.c. life tests.

I agree with the author on the economic effectiveness of

* THORNTON, E. P. G., and BOOTH, D. H.: 'The Design and Performance of the Gas-Filled Cable System', *Proceedings I.E.E.*, Paper No. 2754 E, October, 1958 (106 A, p. 207).

Table A

Influence of Test-Voltage Gradient on Subsequent Life

Gradient of test voltage	Failures resulting from voltage test	Results of life test on surviving samples: Mean life	Minimum / Maximum life	Relative standard deviation from the mean
volts/μ		hours	hours	%
48	0/7	820	336 1 080	36
115	0/7	648	30 1 080	59
153	1/7	542	60 744	47
190	5/7	474	385 572	

Capacitor rating: 1 μF, 400 volts.
Characteristics: tan δ at 1 kc/s = 0·0045, R_i = 25 kilomegohms.
Construction: 3 tissues kraft paper 7μ thick; mineral-oil impregnant.
Duration of voltage test: 1 sec.
Life test: 26·7 volts/μ at 85° C.

elastomer-to-metal case-and-terminal seals, although they should not be classed as truly 'hermetic'.

Mr. T. B. Rolls (*communicated*): The user of shunt capacitors for power-factor correction will not be unduly worried by a fairly high percentage of failures. For instance, if 10% of the capacitors failed during the life of a typical industrial plant, the increase in the power demand would be of the order of 1%, which would not be calamitous. The user will, however, be worried about how the capacitor fails. In any installation it would be inadmissible if the canister of only one capacitor were to explode and wreck the interior of a lighting fitting. Similarly, the failure of 10% of the bobbins in, say, a 100 kVAr capacitor will hardly matter, whereas there would be much concern if the failure of one spoiled a whole tankful.

The paper gives no information to enable the user to forecast the probable life of either new or existing power-factor-correction shunt capacitors in service, nor is there any intimation as to how the life is affected by the various ways in which such capacitors can be used, e.g. switched with their associated plant, controlled by reactive-power relays or left continuously energized.

Professor D. Zanobetti (*Italy: communicated*): The author mentions the application of a short-duration high-voltage test as a method of increasing reliability, both of d.c. and a.c. capacitors, the assumption being that a short stress application might not cause deterioration in the surviving capacitors. However, our experience is that the life always decreases as a result of an increase of the test voltage, whatever the paper quality, thickness and density and the impregnant used, and Table A gives a typical result of a test. A life taken as 100% after the usual voltage test at 2·5 times the rated voltage falls to 75–80% when the test voltage is increased to 6 times, to 65–70% with 8 times and to 55–60% with 10 times the rating.

Both mean and maximum lives decrease; early failures are not eliminated, and the variability of results increases with shortened lives. (In the test shown in Table A we were happy enough not to have failures at the lower voltages, although their occurrence would not have changed the conclusions.) For a.c. capacitors the phenomenon is even more marked, since ionization discharges which may occur during the voltage test are even more damaging.

The very great spread of lives which the author reports, in some cases in a 1 : 20 ratio between shortest and longest lives in a batch, is met only with lower-quality capacitors. A ratio of 1 : 5 should be more representative of standard quality, while ratios of 1 : 2 or 1 : 3 apply for good qualities. This is valid, not only for d.c. and a.c. capacitors, but also for impulse units.

A vacuum of 0·1 mm Hg for the drying and degassing processes should be considered unacceptable by present standaids, the figure of 0·001 mm Hg being by no means exceptional. On the contrary, it tends to be surpassed by good manufacturers, especially for a.c. capacitors. In fact, the studies on ionization suggest that even lower figures are essential for longer life. It is well known that a higher vacuum has no appreciable influence on the electric strength or the insulation resistance but is quite important for loss angle, life and reliability. Table B is, in this respect, self-explanatory.

Table B

Influence of Processing Vacuum on Electrical Characteristics, Life and Reliability

Degassing process vacuum	Loss angle 50 c/s: 20° C	Loss angle 50 c/s: 80° C	Insulation resistance	Electric strength: Mean breakdown	Electric strength: Standard deviation	Life: Test gradient	Life: Mean duration	Life: Standard deviation
mm Hg	%	%	kΩ	V	%	V/μ	hours	%
5 μF capacitors; two tissues 10 μ kraft paper; pentachlorodiphenyl impregnant								
0·1	0·24	0·8	10			17·3	68	55
0·001	0·11	0·7	10			17·3	152	43
0·1	0·24	0·8	10			19	69	54
0·001	0·11	0·7	10			19	135	42
2 μF capacitors; three tissues 9 μ kraft paper; pentachlorodiphenyl impregnant								
(*a*) 0·1	0·32		10	5 030	13	52	152	54
0·001	0·19		17	4 540	11	52	360	31

Samples (*a*), shelf life, 10 years; paper nominally the same; lower insulation resistance due to different terminals insulation. Electric strength tested on three samples only.

THE AUTHOR'S REPLY TO THE ABOVE DISCUSSION

Mr. J. P. Pitts (*in reply*): Mr. Garton mentioned some interesting points in favour of impregnated plastic-film capacitors and it must be emphasized that it is at power frequencies that I see no successor to the paper capacitor for many years. The success of an impregnated-polystyrene capacitor as a competitor at power frequencies seems to depend principally upon economic factors.

In the example mentioned by Mr. Scott, $L/2$ and $5L$ are given as minimum useful lives of associated equipment, and there is an implicit assumption that each of the two types of capacitor with mean lives L and $10L$ has the same form of life distribution. My intention was to suggest that the number of failures occurring during the life of associated equipment, and not the mean life of the capacitor, is the measure of reliability. If, for example, a capacitor was required to give 100 h life under the conditions of operation of a particular guided missile, it would be uneconomic to design for no failure in 10 000 h under these conditions. Nevertheless, I agree that a badly made capacitor, as opposed to a highly stressed well-made capacitor, creates special problems in reliability.

I agree with Mr. Coursey that the economic factor might usefully have been given more emphasis. In this connection, the paper may be thought to have given undue prominence to the elastic type of seal which has a place of importance when viewing present-day paper capacitors as a whole. This type of seal is, however, the result of efforts to get good reliability for many purposes at low cost, and, for a number of important communication applications, a seal with Category H1 performance (notably the soldered-ceramic seal), is chosen (as Mr. Barnard pointed out).

To the best of my knowledge a satisfactory short-term production test for reliability has still to be devised.

The removal of moisture from capacitor tissue and the assessment of dryness are still very contentious subjects. Prof. Zanobetti's comments and Table B are of great interest in this connection, but manufacturers in some countries have evidence of the good reliability over many years of capacitors dried under vacuum in the region of 0·1 mm Hg.

Prof. Zanobetti provides interesting evidence against the short-duration high-voltage proof test with Table A, but it is noted that the test duration was 1 sec in this case.

In reply to Mr. Church and Mr. Jones, I felt that adequate reference to the considerations governing the choice of capacitor tissue could not be made in a general paper. I regret that I have no data available on the migration of silver across silvered-ceramic bushings, mentioned by Mr. Church.

In reply to Mr. Barnard, I feel that the particular subject of metallized-paper-capacitor reliability requires a full-length paper and this would be a most welcome addition to existing literature. The results shown in Figs. A and B are very interesting and reference can be made to a recent paper* by Girling on this subject.

In reply to Mr. Lee, the discharge measurements quoted were made at 25° C. A mean discharge-extinction voltage of 996 volts was obtained initially. After 5 000 h, the lowest discharge-inception voltage was 1 120 volts and on this sample the d.e.v. was then 1 000 volts. These latter figures were not reduced significantly after 10 000 h testing.

Replying to Mr. Stickley, I personally have not seen published data giving a direct comparison of the life-test performance (under identical conditions of test) of similarly constructed and processed capacitors with mineral and chlordiphenyl impregnants.

Without detailed knowledge of the capacitors concerned, it is only possible to guess the cause of capacitance change mentioned by Mr. Chapman. Redistribution of residual moisture in the dielectric is one possible cause.

Mr. Rolls refers to the effects of operating conditions on the life of power-factor-correction capacitors. This subject was not mentioned in the paper but is, of course, of great importance. I suggest that much study is still needed on the behaviour of capacitors under transient conditions of stress.

* GIRLING, D. S.: 'Direct Voltage Instantaneous Breakdown of Oil-Impregnated Paper Capacitors as a Function of Area', *Electrical Communication*, 1958, 35, p. 83.

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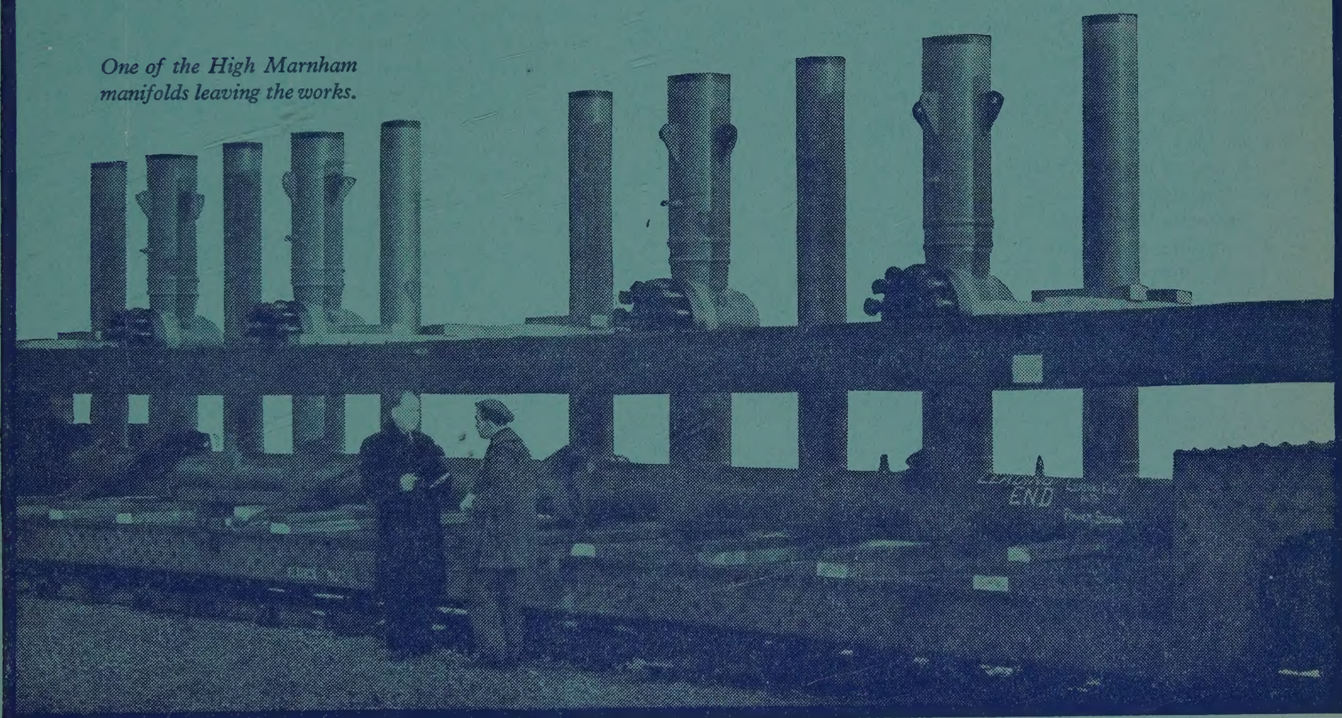
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